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Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons

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Abstract

The present paper deals with the dependence of outdoor thermal comfort on the design of an urban street. The effects of the street vertical profile, including asymmetrical canyon shapes, the use of galleries and further shading devices on the façades, arranged in various orientations are assessed. The study is conducted by means of numerical modelling by using the three-dimensional microclimate model ENVI-met 3.0 which prognosticates the microclimatic changes within urban environments. Thermal comfort is evaluated for the daytime hours across the canyon in high spatial resolution and by means of the physiologically equivalent temperature PET.

The results revealed that all design aspects investigated have a moderate impact on the air temperature and a strong effect on the heat gained by a human body and hence on the resulting thermal sensation. The larger the openness to the sky of the canyon, the higher the heat stress. For canyons with a smaller sky view, the orientation is also decisive: E–W canyons are the most stressful and deviating from this orientation ameliorates the thermal conditions. Basically, galleries and further shading through overhanging façades or vegetation enable a sensitive decrease of the period of time and of the area of thermal discomfort. Yet, this efficiency varies with the orientation and the vertical proportions of the canyon. Therefore, if appropriately combined, all investigated design elements can effectively mitigate heat stress in the summer and promote thermal comfort.

Keywords: Urban canyon; Asymmetry; Gallery; Overhangs; Shading device; Hot–dry climate; Human thermal comfort; Street design; Numerical modelling; ENVI-met; Physiologically equivalent temperature PET

1. Introduction

In urban climate research, which includes thermal, energetic, wind flow and pollution issues, an urban street is typically described as a simple rectangular shape. This is commonly known as the “urban canyon: UC” (e.g. Oke, 1988; Arnfield, 1990a; Givoni, 1997; Asimakopoulos et al., 2001; Arnfield, 2003). The UC is then described by a height-to-width ratio H/W and arranged according to a certain orientation in relation to the sun. In real cases, however, urban street geometry can be more complex (e.g. Moughtin, 2003), as to be asymmetrical, or include design arrangements at street level or on the façades. Indeed, many expressive examples of “textured” streets were designed to cope with stressful climate conditions (e.g. Ravéreau, 1981; Golany, 1982; Herzog, 1996; Krishan, 1996; Moughtin, 2003).

Using galleries as a shading device, for instance, is already known from the antic Greek portico (e.g. Lechner, 1991) and their use is common in hot climate in traditional as well as in contemporary architectures (e.g. Roche, 1970; Golany, 1982; Krishan, 1996; Littlefair et al., 2001). Vegetation was also reported to be climatically effective when implemented in urban streets (e.g. McPherson, 1992; McPherson et al., 1994).

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Moreover, urban streets may have asymmetrical vertical profiles to make the urban buildings climate responsive, i.e. with sufficient winter solar gains in spite of high plot densities. This issue of solar access right has been increasingly addressed (e.g. Knowles, 1981; Pereira and Minache, 1989; Arnfield, 1990a; Givoni, 1997; Asimakopoulos et al., 2001; Capeluto and Shaviv, 2001; Kristl and Krainer, 2001; Littlefair et al., 2001; Pereira et al., 2001; Thomas, 2003; Bourbia and Awbi, 2004). Explicitly, south buildings are set of lower height to allow the opposite north walls facing the sun a large period of exposure to solar irradiation in winter. By contrast, either to shade the façade itself or to protect the street at pedestrian level, the façades are sometimes offset over the street area as can be observed in traditional architectures – e.g. the so-called mucharabiehs in the middle-east region (e.g. Krishan, 1996). These design concepts have inspired the contemporary architecture which increasingly makes use of detail arrangements as climatic control strategies in open spaces (e.g. Capeluto, 2003; Herzog, 1996; Littlefair et al., 2001; Thomas, 2003).

However, the effectiveness of all these strategies has been rarely investigated in relation to climate comfort quantitatively, especially outdoors (e.g. Swaid et al., 1993; Littlefair et al., 2001) and this motivated the recent study of Ali-Toudert (2005), which dealt extensively with these interdependences. First results of this investigation were reported in Ali-Toudert and Mayer (2006) which handled simple symmetrical urban canyons with H/W varying from 0.5 to 4 and arranged in different orientations and simulated for a hot–dry climate. In short, the main findings regarding these symmetrical canyons are as follows:

- Comfort is very difficult to reach passively in the summertime in the subtropics but an improvement is possible through appropriate design.
- Air temperature decreases moderately with increased H/W and wind speed is strongly reduced for perpendicular incidence to street axis, even for large canyons.
- Thermal comfort, expressed in terms of duration, time of day and spatial distribution, is strongly affected by both aspect ratio H/W and solar orientation. This was mainly due to the decisive role of the solar radiation fluxes which are strongly affected by the street geometry. Streets with high aspect ratios and with a N–S orientation ensure the best thermal situation, while wide streets oriented E–W are the most uncomfortable. Increasing the building heights leads to an amelioration of the thermal situation in particular for directions deviating from E–W.
- Shading is the most decisive strategy in mitigating heat stress, and this was confirmed experimentally in other comfort studies (Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007).

Additional arrangements are therefore highly advisable, in particular in pedestrian streets where comfort is required all the day and in the whole area of the street. The present paper presents a second set of results and is concerned with complex geometries, including asymmetrical vertical profiles, galleries, overhanging façades and vegetation. These architectural details are investigated as possible ways to improve further the thermal comfort outdoors under extreme hot summer conditions. The goal is to quantify the contribution of each of these solutions in mitigating the heat stress. The reader is advised to report to the first part of the study, i.e. Ali-Toudert and Mayer (2006) for details on the reference cases, as well as for some theoretical background and methodological aspects. The limits of the model are described in Ali-Toudert (2005) and are mentioned in the present discussion of results when necessary.

2. Methods

One method for assessing thermal comfort outdoors is to conduct field work based on the measurement of all relevant meteorological variables and calculation of energy-based thermal indices (e.g. Mayer, 1993; Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007). Their comparison to data gathered on the basis of social surveys would provide more information on the adaptive behaviour of people (e.g. Nagara et al., 1996; Nikolopoulou et al., 2001; Spagnolo and de Dear, 2003; Stathopoulos et al., 2004). Numerical modelling is another method which is getting increasingly popular (Arnfield, 2003). The latter method was used in this investigation for two main reasons: (1) numerical modelling is particularly suitable in highlighting the connection between the physical urban structure, the microclimate and comfort, making the translation of the results into practical design guidelines easier; (2) it is fast and of low-cost in comparison to extensive measurements and hence allows comparisons between numerous case studies.

Current and well established human-biometeorological methods for assessing thermal comfort outdoors rely on rational indices determined by solving the human energy balance equation. Some well known indices include the predicted mean vote PMV (Jendritzky et al., 1990), the outdoor standard equivalent temperature OUT_SET* (Pickup and de Dear, 1999) and the physiologically equivalent temperature PET (Höppe, 1993, 1999). Calculation of these indices requires readings of the air temperature T_a, air humidity (vapour pressure VP or relative humidity RH), wind speed v and mean radiant temperature T_{mrt}.

ENVI-met 3.0, a three-dimensional numerical model (Bruse, 1999, 2004) was used for the calculation of the microclimatic changes implied by urban geometry. This model was particularly suitable for the purpose of this study: the high spatial resolution allows a fine analysis of the microclimate at street level and the possibility of representing complex geometries including galleries and horizontal overhangs as well as various vegetation covers.

Many studies have reported the dominant effect of T_{mrt}, which sums up the energy gained by a pedestrian, on com-