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Geometry and orientation aspects in passive cooling of canyon streets with trees

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Abstract

As streets usually cover more than a quarter of the urban area, canyon street morphology plays an important role in creating the urban climate. It directly influences the air temperature, moisture and wind flow within the streets as well as the urban surrounding area and has been the topic in several urban climatology studies. Recently, studies based on the street cluster thermal time constant (CTTC) model have been carried out by the authors with a view to assessing the thermal effects of alternative architectural designs of the flanking buildings and inner courtyards. The effect of green spaces, especially that of shade trees which plays a significant role in solar radiation penetration, has not yet been considered. In the CTTC model, passive cooling of the street by solar heating attenuation is governed mainly by the street orientation and its geometry as measured by the aspect ratio of flanking buildings height to street width. The tree shading coverage largely offsets the contribution of these two factors. Moreover, significant thermal effects are provided by the tree canopy, in addition to the direct solar radiation. Accordingly, adjustments are called for in the currently used canyon street models. The present paper discusses the geometry and orientation aspects of the canyon street climate and how these aspects are affected and can be reconciled in the presence of shade trees. Some consequences of environmental design of urban spaces and their effects on outdoor thermal comfort are also considered.

Keywords: Urban climate; Environmental design; Urban street canyon; Shade trees; Architectural climatic design tools; Thermal comfort

1. Introduction

As streets usually cover more than a quarter of the urban area, canyon street morphology plays an important role in affecting the urban climate. Simulations on E–W and N–S oriented streets, using the cluster thermal time constant (CTTC) model, have indicated significant diurnal differences in the urban canopy layer (UCL) air temperature [1]. The CTTC model incorporates several parameters related directly to the physical structure of built forms (building density, shade areas, the cluster geometry, etc.). It has been found to be suitable for predicting the UCL diurnal climatic variations [1,2], in assessing the impacts of anthropogenic factors [3,4] and in evaluating urban design alternatives [3,5,6,7]. In these studies, the effect of green spaces—and especially that of shade trees which plays a significant role in solar radiation penetration—was not considered.

The heat-island problem caused by urbanization enhances the importance of passive cooling [8]. Rosenfeld et al. [9] cite vegetation evapotranspiration and tree shading as an important control measure in heat-island mitigation. In a recent study by the authors [10] on 11 wooded sites in the Tel-Aviv urban metropolitan area (32°N), statistical analysis shows that 80% of the sites' cooling effect is attributable to tree shading.

Use of tree shading in canyon streets necessitates reconsideration of the role of street orientation and geometry in passive cooling. It is readily seen that their contribution is largely obviated by tree shading, but other significant changes are also brought into effect.

The CTTC model is presented in Section 1 of this paper. Section 2 considers the geometry and orientation aspects of the canyon street climate and how these aspects can be reconciled in the CTTC model in the presence of shade trees. Section 3 discusses the importance of the thermal effects induced by the tree canopy in addition to the direct solar radiation, and a way to incorporate these effects in the CTTC prediction model. Section 4 discusses the importance of passive cooling design in urban open spaces on savings in cooling energy and on improving the human thermal comfort. In Section 6, the main effects of shade trees on passive cooling are summarized. Some concluding remarks on design applications and suggestions on further study topics follow. It should be noted that the urban climatic effects discussed in this paper are mainly manifested on calm days.

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Nomenclature

B_r	Brunt number
CTTC	cluster thermal time constant (h)
FA	plan area of building roofs in cluster (m^2)
h	overall heat transfer coefficient at surface ($W/(m^2\,K)$)
H	average height of buildings in cluster (m)
$I_{pen,(t)}$	mean solar radiation intensity incident on ground surface in built-up environment (W/m^2)
$I_{(t)}$	unobstructed solar radiation intensity (W/m^2)
ΔI	step change in solar radiation intensity (W/m^2)
m	solar radiation absorptivity of surfaces
PSA	partial shaded area of open space in cluster
PUSA	partial unshaded area (PUSA = 1 − PSA)
S	plot area (m^2)
SVF	sky view factor of street canton surfaces
t	time (h)
t min	time of minimum temperature (h)
T_a	absolute air temperature (K)
T_s	surface absolute temperature (K)
$T_{(t)}$	air temperature (°C)
$\Delta T_{AHR,(t)}$	contribution of anthropogenic heat to air temperature (K)
$\Delta T_{NLWR,(t)}$	contribution of net long wave radiation exchange to air temperature (K)
$\Delta T_{SOLAR,(t)}$	contribution of solar radiation absorption to air temperature (K)
$\Delta T_{(t)}$	air temperature change at time t (K)
VP	partial vapor pressure (mmHg)
W	average width of streets in cluster (m)
WA	external buildings' walls area in cluster (m^2)

Greek letters

ε	ground surface thermal emissivity (about 0.92)
λ	time (h)
σ	Stefan–Boltzmann constant ($=5.67\times10^{-8}$ W/m^2)

2. The CTTC model

For the convenience of the reader, we give here a summary of the main features of the analytical CTTC model. A detailed description can be found in earlier articles [1,2].

In the CTTC model, the predicted air temperature of a cluster is calculated through the contribution of the heat received from external sources, mainly net solar radiation and anthropogenic heat-release. The predicting equation for the rise in air temperature from sunrise (minimum temperature) to any hour t of the day derived by Swaid and Hoffman ([1]; p. 328, Eq. (7)), is as follows:

$$\Delta T_{(t)} = (\Delta T_{SOLAR,(t)} - \Delta T_{SOLAR,(t\,min)}) - (\Delta T_{NLWR,(t)} - \Delta T_{NLWR,(t\,min)}) + \Delta T_{AHR,(t)} \quad (1)$$

where $\Delta T_{SOLAR,(t)}$ is the contribution of direct solar radiation to air temperature variations.

$$\Delta T_{SOLAR,(t)} = \frac{m}{h}\sum_{\lambda=0}^{\lambda=t}\Delta I_{pen(\lambda)}\left(1 - \exp\frac{-(t-\lambda)}{CTTC}\right) \quad (2)$$

The mean direct solar radiation incident on the ground surface, is as follows,

$$I_{pen,(t)} = I_{(t)}(1 - PSA(t)) \quad (3)$$

where PSA is the partial shaded area at time t (see list of symbols for the other parameters).

The CTTC parameter, which acts as an attenuating factor in shaping the air temperature, is a function of the properties of the cluster's construction materials, and of its building geometry,

$$CTTC = \left(1 - \frac{FA}{S}\right)CTTC_{ground} + \frac{WA}{S}CTTC_{walls} \quad (4)$$

The CTTC of the ground and walls are estimated at about 8 and 6 h, respectively ([1], op. cit.). The contribution of the net outgoing long wave radiation flux to air cooling obeys the Stefan–Boltzmann law:

$$\Delta T_{NLWR,(t)} = \frac{(\sigma\varepsilon T_s^4 - \sigma B_r T_a^4)SVF}{h} \quad (5)$$

where T_s and T_a are surface and air absolute temperatures, respectively, B_r is the Brunt atmosphere equivalent emissivity (magnitude of about 0.65) which depends on the air water pressure [1,2] and, SVF the sky view factor, a function of the street's geometry. In a canyon-type street, SVF = cos (arctan (2H/W)), and H/W is the street aspect ratio. $\Delta T_{NLWR,(t)}$ is almost constant day and night in normal weather periods.

From a set of measurements carried out on five calm days in a sunny open square of Ramat-Gan (Tel-Aviv metropolitan area 32°N), on a typical summer (July) day at noon, the measured ΔT from sunrise to noon was: 7.60 K (24.2 °C at 6:00 h and 31.8 °C at 15:00 h).

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

$$\Delta T_{SOLAR,(t)} = 8.68\,K\ (1.3\,°C \text{ at } 6{:}00\,h \text{ and } 9.98\,°C \text{ at } 15{:}00\,h);$$

$$\Delta T_{NLWR,(t)} = 0.92\,K\ (10.3\,°C \text{ at } 6{:}00\,h \text{ and } 11.2\,°C \text{ at } 15{:}00\,h);$$

$$\text{calculated} = 7.76\,K\ (8.68\,K - 0.92\,K).$$

The aspect ratio (H/W) of the measured square is 0.480 and SVF is 0.721.