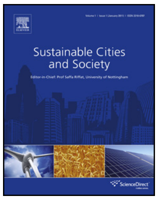
Sustainable Cities and Society 13 (2014) 254–266

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Cool materials impact at district scale—Coupling building energy and microclimate models

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ARTICLE INFO

Keywords:
Urban microclimate
Building energy demand
Weighting factor method

ABSTRACT

As of 2007, more than half of the world's population now lives in urban areas and their activities have led to an increase in building energy demand, notably in summer. The higher temperatures in densely built areas are mainly due to landscaping and anthropogenic heat fluxes such as air conditioning systems. Acting on urban landscaping, building density, surface albedo and green areas can mitigate the urban heat island effect, with a direct and indirect improvement of building energy performance.

In the present study, a new numerical approach has been developed to assess building energy demand, including microclimate interactions on buildings. The different physical phenomena were computed at the district scale, with different meshes, for the surfaces and volumes of the tridimensional numerical mockup. The urban microclimate was assessed using specific models developed for outdoor airflows, and longwave and shortwave radiative exchanges. The thermal behavior of buildings was computed using a model that is based on the weighting factors method, which saves computation time. The thermal balances, including indoor and outdoor balances, were computed simultaneously for the whole district cells for each time step.

The case study we selected was based on a district located in Nantes, France, named Pin Sec. A parametric study was carried out on cool materials and the results were displayed as the cooling demand of buildings for each case studied. The impact of cool materials on both building energy demand and urban microclimate are clearly demonstrated by the results we obtained.

1. Introduction

Between 1950 and 2007, the urban population grew from 30% to 50% of the world's population. The associated growth of urban areas has amplified urban microclimate development. The best known urban microclimate phenomenon engendered is the Urban Heat Island (UHI), characterized by higher temperatures in urban areas than in rural areas. The Urban Heat Island is a complex phenomenon that is the result of many factors (Oke, Johnson, Steyn, & Watson, 1991):

- Urban street canyon geometry, which induces radiation trapping. The longwave radiation losses toward the sky are reduced, and multiple reflections of shortwave radiation decrease the effective albedo, increasing solar irradiation trapping.
- The Urban greenhouse effect, which is increased by longwave irradiation from the polluted and warmer urban atmosphere.
- Thermal properties which increase storage of sensible heat in the fabric of the city.
- Anthropogenic heat released from human activities (traffic, industry, etc.).
- Diminution of evapotranspiration due to a reduction in the evaporation surface in the city.
- Wind shelters, resulting from urban morphology, which reduce turbulent heat transfer.

UHI can mitigate the heating energy demand in winter, while the cooling energy demand during summer is increased (Santamouris et al., 2001). Moreover, the use of cooling systems increases urban anthropogenic heat during the most critical periods. The result is a negative feedback that increases the UHI and the building energy demand and leads to oversized air-conditioning systems. In the search for alternative solutions to improve thermal

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http://dx.doi.org/10.1016/j.scs.2014.02.002
2210-6707/

Nomenclature

Greek characters

ρ	air density, kg/m^3
$\varphi_{ce,i}$	convective heat flux at the outside wall surface, W/m^2
$\varphi_{ci,i}$	convective heat flux at the inside wall surface, W/m^2
$\varphi_{pe,i}$	transmitted conductive heat flux at the outside wall surface, W/m^2
$\varphi_{pi,i}$	transmitted conductive heat flux at the inside wall surface, W/m^2
$\phi_{k,n}$	heat flux through a cell interface (index n) and from an air cell (index k), W
ϕ_s	heat production in the cell, W

Latin characters

A_i	area of the wall indexed i, m^2
C_p	air specific heat capacity, J/(kg K)
D_v	ventilation air mass flow, m^3/s
E	excitation used for the calculation of weighting factors ${TS_{E,i}}^n$
$h_{ci,i}$, $h_{ce,i}$	convective heat transfer coefficient inside and outside the wall i, W/(m^2 K)
$I_{SWe,i}$	outside solar irradiance on the wall facet i, W/m^2
$I_{SWi,i}$,	inside solar irradiance on the wall facet i, W/m^2
$I_{LWe,i}$	outside longwave irradiance on the wall facet i, W/m^2
$I_{LWi,i}$	inside longwave irradiance on the wall facet i, W/m^2
N_n	interface number for a canopy cell i
N_p	number of external walls of a building cell
P	cooling or heating need to maintain the set point temperature, W
Q_n	air mass flow through the interface n, kg/s
Q_{int}^t	internal heat gains, W
Q_E^t	thermal load due to the excitation E, W
$T_{e,i}^t$	air temperature of the canopy cell i at the time t, °C
$T_{si,i}^t$	inside surface temperature of the wall i at the time t, °C
$T_{se,i}^t$	outside surface temperature of the wall i at the time t, °C
$TS_{E,i}^n$	weighting factors for the inside surface temperature i
U_w	thermal transmittance of windows, W/(m^2 K)
u_0	horizontal air velocity at the boundary condition, m/s
u_{ref}	meteorological wind velocity, m/s
u, v, w	wind velocity components along x, y and z, m/s
V	volume of a building cell, m^3
V_k	volume of a canopy cell (index k), m^3
X_i^n, Y_i^n, Z_i^n	response factors defined for the wall i, W/(m^2 K)
z, z_{ref}	altitude and altitude of the meteorological wind, m
z_0	rugosity length, m

comfort and to reduce cooling energy demand, the urban environment can be designed to mitigate UHI and its consequences. A modification of urban landscaping, such as building morphology (Chen, Ooka, & Kato, 2008; Johansson, 2006), surface albedo (Akbari, Bretz, Kurn, & Hanford, 1997; Bretz, Akbari, & Rosenfeld, 1998; Djedjig, Bozonnet, & Belarbi, 2013; Doya, Bozonnet, & Allard, 2012; Picot, 2004; Robitu, Musy, Inard, & Groleau, 2006; Saxena, 2002; Taha, Akbari, Rosenfeld, & Huang, 1988) or green areas (Akbari, Kurn, Bretz, & Hanford, 1997; Yu & Hien, 2006; Yu & Hien, 2009) can mitigate the UHI, which consequently reduces energy demand. Thus microclimatic considerations should be taken into account in urban planning. A simulation of the different physical processes that exist in urban areas would help urban planners determine the best urban landscapes in order to optimize building energy efficiency (Capeluto, Yezioro, & Shaviv, 2003) and to improve outdoor thermal comfort (Pattacini, 2012).

Many different tools have been developed to model building energy demand or urban microclimate. Conventional building energy simulation (BES) tools such as TRNSYS (Klein et al., 2010), CODYBA (Roux, 1984) and EnergyPlus (Crawley, Lawrie, Pedersen, & Winkelmann, 2000) are traditionally used for energy performance assessment. Usually, in these models, one calculus node is attributed to each wall with a specific orientation and thermal properties, depending on the layers. BES tools give the detailed indoor thermal conditions and energy demand required to maintain occupant comfort. They could be used to optimize the energy consumption of a building by computing annual or seasonal building energy demand. The meteorological data files used are generally obtained from standard data (like an airport) and are not representative of urban microclimate conditions. Outdoor physical phenomena are generally very briefly described and the interaction with the urban environment is not taken into account.

Various microclimatic models have been developed to compute the physical processes that are present in urban areas (Martilli, 2007). A first category focuses on the impact of radiative exchange on building energy demand. These models are used to study the solar and longwave exchange between buildings and their environment, taking into account urban morphology. Asawa used a 3D-CAD description of a building and its environment in a radiative and a conductive model (Asawa, Hoyano, & Nakaohkubo, 2008). This was applied to each mockup element and the building energy demand was computed. This model was used to compare the impact of size or distance from neighboring buildings or trees on the energy demand of one building during the course of one day (He, Hoyano, & Asawa, 2009). Similarly, the CitySim model developed by Robinson gives the building energy demand for each building in a district using a simplified building energy model and a district radiation model (Robinson, 2009). This model can be used to compare quickly different urban morphologies in order to optimize the impact of solar irradiance over one year (Kämpf, Montavon, Bunyesc, Bolliger, & Robinson, 2010; Kämpf & Robinson, 2010).

A second category adds the simulation of thermo-aeraulic phenomenon to the radiation phenomenon. By coupling the radiative district model SOLENE (Miguet & Groleau, 2002) with a CFD model, Bouyer evaluated the energy demand of one building in a new district in Lyon, France, over one week in winter and one week in summer (Bouyer, Inard, & Musy, 2011). This approach was used to compare two types of urban landscape, a full mineralized case study and a vegetated case study. The green case study led to a 9% reduction in cooling energy demand. The Envi-met three-dimensional model (Bruse, 2006) can be also included in this category. This non-hydrostatic microclimate model is designed to simulate the surface–plant–air interactions in an urban environment and provides an interaction analysis between urban microclimate and urban landscape. It was coupled with the BES software EnergyPlus (Crawley et al., 2000) to model the building energy demand of a building in Guangzhou in China during 3 days in summer and 3 days in winter (Yang, Zhao, Bruse, & Meng, 2012). This approach was compared with a building energy demand simulation without taking into account the interaction with the environment, and revealed a difference of 16%. Envi-met was used to study the influence of an urban park on its environment (Yu & Hien, 2006). The diminution in ambient temperature due to the park impacted on the closest buildings, leading to an indirect reduction in the computed cooling energy demand.

These models provide a very precise description of the different thermal processes operating in an urban area. Yet the description of