Building and Environment 73 (2014) 162–170

Contents lists available at ScienceDirect

Building and Environment

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

Comparative assessment of various heat island mitigation measures

Saba Saneinejad [a,*], Peter Moonen [a,b], Jan Carmeliet [a,b]

[a] ETH, Swiss Federal Institute of Technology Zürich, Wolfgang-Pauli-Strasse 15, 8093 Zürich, Switzerland
[b] Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland

ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form
2 December 2013
Accepted 22 December 2013

Keywords:
Heat island
Evaporative cooling
Albedo
Shading
Street canyon
Thermal comfort

ABSTRACT

With the rapid intensification of urban heat islands worldwide, measures for its mitigation are gaining attention. Some of the most popular measures are based on employing evaporative cooling, altering the surfaces' albedo or making use of shading. In this paper, we numerically investigate the influence of each of these three methods on the comfort of a pedestrian in a typical urban street canyon. The environmental conditions in the urban street canyon are obtained from a detailed microclimatic model, and serve as input for a comfort model based on the Universal Thermal Climate Index (UTCI). Simulations are conducted for average summer conditions, taken from a typical meteorological year (TMY), and for heat wave (HW) conditions. The results show that evaporative cooling can considerably reduce the air temperature and the mean radiant temperature, but that the corresponding increase in vapor pressure limits the net gain in comfort. Shading results in significantly reduced surface temperatures, in addition to decreasing the intensity of direct solar irradiation, both leading to an increased comfort sensation. Increasing the local albedo of urban surfaces also leads to lower surface temperatures, but does not affect the amount of direct solar irradiation, explaining the lower comfort gain compared to shading. The cooling effect of all methods proved to increase during a HW in comparison to a TMY. These observations show that the effectiveness of mitigation measures highly depends on the climatic conditions and demonstrate the potential of microclimatic models to determine the optimal combination of measures for a given context.

1. Introduction and motivation

Climate change and continuing urbanization result in increased air temperatures in densely built urban areas in comparison to the surrounding rural hinterland. This phenomenon is called the "urban heat island" (UHI). Measurements taken at approximately 30 urban and suburban areas as well as in 10 urban street canyons in Athens, showed a doubling of the cooling load and a tripling of the peak electricity load for cooling [1] due to the UHI. In addition to affecting the energy demand, increased air temperatures in urban areas lead to heat stress, which causes discomfort along with reduced mental and physical performance, as well as physiological and behavioral change [2].

Considering the adverse consequences of the UHI, a vast amount of research has been directed towards its mitigation. Some of the suggested measures are the use of high albedo surfaces [3–5], evaporation from porous surfaces [4,6–10], evaporation from ground-level water surfaces [11] and roof ponds [12,13], vegetated surfaces [14], rooftop gardens [15], and trees [3,5,16]. These and other studies have in common that they focus on the impact of a specific class of mitigation measures, and show their capability to reduce surface and air temperature, UHI intensity and/or building energy demand. A direct comparison of published results is however not possible, as all studies involve different sets of simplifying assumptions, are conducted for different climatic conditions, and employ a different metric to quantify the performance of the investigated measure.

In this paper, we present a detailed inter-comparison between three major classes of mitigation measures for the same urban configuration and using the same performance metric. We will demonstrate that the performance of the different measures greatly depends on the urban context and on the local climatic conditions, and hence that it is needed to select and optimize measures based on the specific context in which they will be implemented. The investigated mitigation strategies are (i) evaporative cooling, (ii) maximizing albedo, and (iii) shading. Many other mitigation strategies, such as planting trees, can be considered as a combination of these three basic strategies. The

---

* Corresponding author. Tel.: +41 58 765 4702; fax: +41 44 6331041.
E-mail addresses: saba.saneinejad@alumni.ethz.ch (S. Saneinejad), peter.moonen@empa.ch, moonen@arch.ethz.ch (P. Moonen), jan.carmeliet@empa.ch, carmeliet@arch.ethz.ch (J. Carmeliet).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.12.013

investigated urban configuration is the widely-studied street canyon, which can be considered as a generic element of the urban canopy. The selected performance metric is the comfort sensation of a pedestrian, standing in the street canyon. In this study, the outdoor comfort is evaluated by means of the Universal Thermal Climate Index (UTCI), which accounts for the effects of temperature, humidity, wind speed and radiation intensity [17]. These parameters are obtained from a detailed simulation using the urban microclimate model developed by the authors [18,25]. To arrive at a balanced evaluation of the different mitigation measures, simulations are conducted both for typical summer conditions and for heat wave conditions.

The remainder of the paper is structured as follows. In the next section the main features of the urban microclimate model and the comfort model are shortly reviewed (Section 2). Next, the investigated configuration is described in detail (Section 3). In Section 4 the effect of the individual mitigation strategies on human comfort is analyzed, the results are inter-compared and reasons for the observed performance differences are given. Finally some general conclusions are drawn (Section 5).

2. Model for comfort assessment in the urban microclimate

2.1. Microclimate model

The urban microclimate model consists of three coupled and interacting sub-models. A brief description of the individual sub-models is given below. More detailed information on the model and its validation can be found in Saneinejad et al. [18,25].

- A **Computational Fluid Dynamics (CFD) model** is employed to calculate the temperature, relative humidity and wind flow pattern in the urban environment. As wind speeds inside an urban area can be low, buoyancy effects are taken into account in this model. The CFD simulations are performed using the commercial software package Ansys-Fluent 12.0 which uses the control volume method to discretize and solve the mass conservation equation and the Reynolds-Averaged Navier–Stokes (RANS) equations [19]. Closure is obtained using the well-known realizable k–ε turbulence model. Based on the validation work of Blocken et al. [20], Defraeye et al. [21] and Xie et al. [22], near-wall modeling is based on Low Reynolds Number Modeling (LRNM) rather than the less accurate (yet more commonly used) wall function approach. Second-order discretization schemes as well as the SIMPLE algorithm for pressure–velocity coupling are employed. Pressure interpolation is also second order.
- An in-house developed **Building Envelope Heat and Moisture (BE-HAM) model** is employed to simulate the hygro-thermal behavior of the porous building materials and the pavement. This model solves the coupled balance equations governing transport and storage of heat and moisture (i.e. vapor and liquid) in porous materials by means of the finite element method. A detailed description of the model, the underlying assumptions and the model validation can be found in Janssen et al. [23], Defraeye [24] and Saneinejad [25]. Important to note is that latent heat due to phase change and enthalpy transport, due to vapor diffusion in the material and at the surface, is explicitly taken into account in this model in order to accurately account for evaporative cooling.
- An in-house developed **radiation (RAD) model** is employed to solve the heat balance for short-wave and long-wave radiative exchange between the urban surfaces and the sky. The radiation model accounts for multiple reflections by employing Gebhart factors [26,27]. Specular reflection of direct solar irradiation is not considered in the model. The radiation model was verified by comparison with the building energy simulation model TRNSYS 17.0 [28] for a benchmark problem.

The heat and mass fluxes, obtained from the CFD, BE-HAM and RAD models, have to be in equilibrium along exterior surfaces. This can be expressed by the following conditions:

$$q_m = q_{c,m,w} \tag{1}$$

$$q_h = q_{c,h,w} + q_{rad} + (L_v + C_v T)q_{c,m,w} \tag{2}$$

where q_m (kg/m^2 s) is the total mass flux inside the material (BE-HAM), here balanced by evaporation $q_{c,m,w}$ (kg/m^2 s) at the surface (CFD), and q_h (W/m^2) is the total heat flux inside the material (BE-HAM), balanced by convection $q_{c,h,w}$ (W/m^2) at the surface (CFD), combined short and long-wave radiation q_{rad} (W/m^2) (RAD), and evaporation $q_{c,m,w}$ (CFD). The latter component accounts for latent heat transport by accounting for: i) vapor transport via the specific heat capacity C_v (1880 J/kg K) and ii) phase change via the latent heat of evaporation L_v (2.5 × 10^6 J/kg). T (K) is the absolute temperature.

The different heat and mass flux components in the surface balance equations (1) and (2) are separate outputs from the three individual sub-programs, but are highly dependent on each other. This necessitates adopting an iterative solution procedure. The employed **coupling strategy** consists of three steps. First, the BE-HAM model conducts a transient simulation from time t to time $t + \Delta t$ and passes the surface temperatures to the RAD model. Next, The RAD model calculates the long-wave and short-wave radiative heat balance at the surfaces and returns the updated radiative heat fluxes to the BE-HAM model. These two steps are repeated until those surface temperatures are found for which the heat balance at the surface is satisfied. The converged surface temperatures as well as the corresponding moisture contents at the interfaces between the air domain and the porous domain are then passed from the BE-HAM model to the CFD model and a steady-state CFD simulation is performed. The resulting distribution of the convective heat and mass fluxes at the porous surfaces serves as input to the next time step Δt. The magnitude of this time step is of utmost importance, and is determined based on a sensitivity study. For the investigated cases a time step of 120 s was found adequate. A detailed discussion on the coupling strategy and its validation can be found in Ref. [25].

2.2. Comfort assessment

The microclimate model is supplemented with a model to evaluate the comfort conditions in the urban area. It is well-known that human thermal comfort is influenced not only by temperature, but also by relative humidity and wind [29]. Different mitigation strategies could influence these factors in different ways. Therefore it is important to consider their combined effect on human comfort, using a comfort index specifically developed for outdoor environments. In this study, we employ the Universal Thermal Climate Index (UTCI) [17]. The UTCI is expressed as the air temperature of a reference environment, leading to the same physiological response of a reference person as the actual environment. In the reference environment, the mean radiant temperature is equal to the ambient air temperature, the relative humidity is 50% for an ambient reference temperature below 29 °C and is set corresponding to a vapor pressure of 20 hPa for higher ambient reference temperatures, and the wind speed measures 0.5 m/s at 10 m height [17]. For the reference person, a metabolic rate of 135 W/m^2 and a walking speed of 1.1 m/s are considered.