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Impact of radiation exchange between buildings in urban street canyons on space cooling demands of buildings

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ABSTRACT

There is worldwide a trend towards urbanization, and cities try to improve their sustainability by saving natural resources and energy, and to mitigate the impact of climate change. Therefore growing cities need to optimize the energy demand of their new and existing buildings. There are a large number of urban scale phenomena that influence the energy demand of buildings. One of the most important influencing phenomena is the shortwave solar and longwave radiation exchange within an urban environment. It was demonstrated that the influence of neighbouring buildings has to be considered in detail to predict correctly the building energy demand. In this study, space cooling demand of stand-alone buildings is compared with buildings in an urban street canyon configuration. Detailed radiation models for the solar and longwave radiation are used to determine the radiation exchange between the buildings. The results show a strong influence of neighbouring buildings on the space cooling demands. This influence is strongly dependent on the shading device control strategy incorporated in the building energy management. Counterintuitively the space cooling demands are in some cases are higher for low values of solar irradiance, because the shading device control directs the devices to remain open during longer time periods when irradiance values are low, leading to higher total solar gains through the windows.

1. Introduction

The part of the population living in urban areas is continuously increasing. During the past two decades globally the part of the population living in urban areas increased from 45% to 54% and will further increase to 67% by 2050 [26]. In more developed regions (Europe, Northern America, Australia/New Zealand and Japan) the urbanization is even more pronounced with currently 78% of the population living in urban areas increasing to 86% by 2050. Residential and commercial buildings consume together roughly 40% of the final energy consumption in the EU [7]. Almost 70% of the residential energy consumption is consumed for heating and cooling. Therefore there is a great energy saving potential by minimizing the energy demand of buildings in urban areas. Buildings in urban areas are influenced by the local microclimate that differs significantly from the rural microclimate. The air temperatures are higher due to the urban heat island effect and the wind speeds are lower due to wind sheltering by buildings [16,20]. Measurements in London showed up to 7 K higher air temperatures at night-time in the city compared to measurements outside the city [28]. In Athens the urban heat island intensity exceeds 10 K, what may lead to a doubling of the space cooling loads and triplication of the peak electricity load for space cooling purposes [21]. The space cooling loads in urban areas is expected to further increase due to global warming and increasing urban heat island intensities caused by urbanization [6]. The increase in the occurrence of heatwaves [22,9] will cause an even stronger increase of the peak cooling loads compared to the increasing annual loads.

Due to urbanization, the urban heat island effect and global warming, it is important to optimize buildings in terms of energy demand considering local urban microclimates. The commonly used building energy simulation (BES) models were developed for stand-alone buildings [11]. Recent studies show that building energy demand simulations should take into account the influence of neighbouring buildings for the radiation and convective heat

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transfer as well as for the urban heat island intensity (e.g. [1,4]. Neighbouring buildings may strongly influence the energy demand for space cooling and heating, and daylighting by shadowing and multiple reflections of the solar radiation. Stromann-Andersen and Sattrup [24] found that the total energy consumption of buildings increases due to the fact that the urban density affects the daylight availability and passive solar gains. Solar gains have an important impact on the space cooling demands of buildings and are commonly minimized by using shading devices. There is a large energy saving potential for optimization of shading devices and their control strategies. Bellia et al. [3] showed that for an office building in Palermo 20% of the global annual energy can be saved by using suitable shading devices. For buildings in urban areas, besides the shading devices, also neighbouring buildings influence the solar gains. Muhaisen and Gadi [15] and Yasa and Ok [30] compared the energy demand of courtyard buildings for different courtyard proportions. They concluded that self-shading has a significant impact on the building energy demand. Also a number of studies on the influence of shading device control strategies on the energy demand have been conducted. Tzempelikos and Athienitis [25] studied amongst others the influence of control for shading devices on the energy demand of office spaces in Montreal (Canada). They concluded that with a shading pattern that has an optimal balance between solar gains and internal gains, the total annual energy demand can be reduced by 12%. In a similar study Zhang and Lam [31] analysed the impact of two window shading control strategies on thermal and lighting loads of office buildings for different climates in the United States. They showed a reduction of the total loads of 6.7% for internal shading devices with an optimal control strategy (note that with external shading devices a stronger decrease of solar gains can be achieved). In reality the shading devices are often not used in an optimal way, because they are either not automated or overruled by the occupants. Correia da Silva et al. [5] monitored the occupant's interaction with electric lighting and shading systems for offices in Porto (Portugal). The results showed that lighting and shading control were influenced more by occupational dynamics than by the environmental conditions. Most of the opening events for the shading devices occurred at the moment of the first arrival and most of the closing events at the moment of departure, only 37% of the opening and closing events occurred in between.

Although the physics of radiation is well understood and can be described correctly, the radiation exchange in an urban environment is commonly not modelled in a detailed way in BES. The radiation exchange is commonly strongly simplified, due to the reason that when the geometry is complex, more advanced numerical methods are needed to determine view factors for estimating the exchange of longwave and diffuse shortwave radiation. Evins et al. [8] concluded in their paper that there is no BES program that allows assessing the radiation exchange between buildings in a straightforward manner. They also showed the importance of considering longwave radiation exchange between buildings in sufficient detail.

In this study the impact of the radiation exchange between buildings in urban street canyons on space cooling demands is studied. Further the results for different shading device control strategies are compared, with a focus on the solar gains through windows by reflection with neighbouring buildings. Additionally, the influence of different building orientations and ground surface covers is studied. BES with detailed radiation models for both short- and longwave radiation are conducted. The aim of this paper is to show how space cooling demand depends on the building surroundings and the control strategy of the shading devices. Results for three different shading device control strategies are compared. The control strategies used in this study are simplified models of actual shading device control strategies, since detailed information on the control strategy and their input parameters are often missing, and the implementation of the overruling of the control systems by the occupants is difficult [5]. The focus of this study is therefor on the relative influence of the predicted space cooling demands on the used model for the control strategy, rather than wanting to analyse absolute values of the space cooling demands for different control models.

The structure of the paper is as follows. In Section 2 the numerical model and simulation methods are presented. The space cooling demands are analysed in Section 3.1. In Section 3.2 the shortwave irradiances on the façades for different cases are studied. In Section 3.3 and 3.4 the solar gains through windows for different the shading device control strategies are discussed. In Section 4, the obtained results are discussed critically and in Section 5 conclusions are drawn.

2. Numerical model and simulation method

For the Building Energy Simulation (BES), the program CitySim [12,10] is used. A verification of CitySim was done using the BESTEST [27]. CitySim models the energy fluxes in a city, with size ranging from a small neighbourhood to an entire city. Detailed radiation models for solar and longwave radiation are implemented in CitySim, accounting for radiation exchange between neighbouring buildings, ground and environment. To compute hourly irradiance of short and longwave radiation on building surfaces, the Perez All Weather model [17] and a Simple Radiosity algorithm [18] are used. Multiple iterations for the radiation calculations are performed to avoid numerical instabilities. The heat flow through the walls is determined with a model based on the analogy with an electrical circuit (resistor-capacitor network). Because the windows are not represented geometrically, no window surface temperature is determined separately, although heat conduction through the windows is considered. For the convective heat transfer coefficients, correlations by McAdams [13] are used. More sophisticated approaches, considering results from CFD flow simulations [2], are not considered in this model. To get individual surface temperatures for the individual façades and the roof of a building, each building is modelled as composed of several thermal zones, each consisting of exterior building walls (or roof) and the associated part of the building volume. CitySim also includes HVAC and energy conversion system models [19]. In contrast to the standard CitySim version, in the version used here, a heat balance is solved for the ground surfaces between the buildings. This heat balance includes shortwave and longwave radiation and storage of heat as well as heat conduction to the soil. Evapotranspiration from green surfaces is not included. To model the heat storage and heat conduction in the ground, a number of ground layers are defined with thickness, heat conductivity and heat capacity as input parameters.

The simulations presented in this paper are conducted for standalone and buildings in a street canyon configuration (Fig. 1)for the climate of Zürich (Switzerland). For the simulations a Typical Meteorological Year (TMY) from Meteonorm [14] is used. Two different ground surfaces are modelled around the buildings: grass and asphalt. For asphalt, the above described soil model is used. For grass the surface temperatures are obtained from Meteonorm [14], since evapotranspiration is not considered in CitySim. The solar reflectance for asphalt is 0.16, which is lower compared to grass (0.2).

All buildings are modelled as office buildings with standard occupancies and internal gains according to SIA [23]. Ventilation and infiltration are considered. The walls (with outer insulation) have a U-value of 0.25 W/m^2K, the floors have a U-value of 0.3 W/m^2K and the roofs have a U-value of 0.29 W/m^2K. The windows have a U-value of 1.1 W/m^2K and a G-value of 0.7 and the glazing fraction of the buildings is 50%. All façades have a solar