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Impact of shortwave multiple reflections in an urban street canyon on building thermal energy demands

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ABSTRACT

The urban fabric plays a fundamental role in convective and radiative heat exchanges between buildings. The main parameters which influence these heat exchange mechanisms are due to climate conditions such as air temperatures/humidity, wind speed/direction and solar irradiance. These weather data are related on where our cities are located rather than on how they are built. In this work, a building energy simulation tool is exploited to study the impact of multiple shortwave inter-reflections exchanges in an urban environment with the aim of evaluating their influence on the thermal energy demand of a building. These multiple radiative exchanges modify the buildings envelope energy budget influencing space cooling and heating demand. A street canyon model validated in a previous work was used to investigate the effects of the urban radiative trapping. Due to multiple shortwave reflections, the effective solar radiation absorbed by the buildings envelope surfaces is higher than in a street canyon building where only shadowing phenomena due to canyon geometry are considered. A comparison has been performed between these two configurations as a function of several driving parameters such as street canyon aspect ratio, orientation, transparent/opaque surfaces ratio and solar absorption. The goal is to characterize how these parameters influences the inter reflections inside an urban canyon and thus the buildings energy demands. Increases in cooling demand up to 35% and decreases in heating demand up to 7.5% are found.

1. Introduction

Energy saving is an important priority in developed countries where a substantial part of energy consumption is represented by buildings. In recent years, several efforts have been made worldwide to improve the energy efficiency of buildings [1] and for this reason several policy measures aimed at saving energy were discussed. In the European Union (EU), buildings account for about 40% of total energy consumption and represent the largest sector of all areas destined for end users. For this reason, the "Building Energy Efficiency Directive" [2] was introduced to impose different requirements for new and existing buildings within the EU.

To fully address this topic, it must be considered that a building is a system whose borders exchanges thermal energy with the surrounding environment. It means that urban areas conformation influences local microclimate, introducing differences in the boundary conditions compared to those occurring outside of the city, in rural areas. In this regard it is known, as confirmed by several studies, that the urban heat island (UHI) phenomenon plays an important role for what concerns the air temperature increase in the urban environment [3] and thus an alteration in energy use [4–6]. The local urban configuration produces some unwanted effects such as: (i) wind speed lowering, (ii) increasing of surface solar loads due to multiple inter-reflections and (iii) lack of evapotranspiration of the ground.

A study on energy consumption trends in Taiwan showed that energy consumption in urban areas is 81% higher than in rural areas [7]. According to the past literature, the density of the building [8], the shape and orientation of the road [9,10] the presence and the type of vegetation [11–13] and the properties of the materials of the surfaces in the canyons [14–16] represent factors that influence the urban thermal environment. In short, the mutual interaction between buildings and urban environment generate the worsening of operative conditions. For this reason, a holistic approach in the definitions of design choices for new and existing buildings is required to reach a smart planning for modern cities [17,18]. Building energy simulation codes (BES) are often used to estimate and predict the energy consumption of a building and the outdoor thermal conditions. Most energy simulations are performed considering a single isolated building [19] using a typical meteorological year (TMY) which does not account of the urban microclimate,

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since they were obtained from weather stations located in most cases in rural or suburban areas. Therefore, it is necessary to impose conditions that modify the TMY with the real conditions of the microclimate [20]. The evaluations made in this work, which imply the modeling of mutual inter-reflections between surrounding buildings, are aimed at the investigation of one of the phenomena which contributes to UHI effect and thus to the definition of the local microclimate influenced by the urban configuration.

Recently, some researchers have begun using BES to study the space cooling demands of buildings, modeling their urban context more accurately, especially for what concerns radiations exchange [21]. The integration or coupling of BES and computational fluid dynamics (CFD) has been exploited to better simulate the outdoor environment [22]. In some simulation tool, it is possible to account of the effect, on the studied building, of the shadings due to the surrounding buildings. In [23] the authors accounted for shadowing and reduced ground reflectance founding a lower heating demand with increasing density of neighborhood. Anyway, many BES programs do not model in detail the radiative exchanges between buildings' surfaces in the urban context. The actual behavior of the built environment for what concerns radiation exchange is basic both for shortwave and for longwave radiation. In fact, it was demonstrated [24] that solar and longwave radiation reflected by urban surfaces in the surrounding environment have a strong impact on space heating demand and space cooling demand.

The objective of this study is to evaluate how shortwave multiple reflections affect thermal energy demand (cooling and heating) of a street canyon building as a function of canyon aspect ratio, orientation, transparent/opaque envelope surfaces ratio and surface absorption factors. For this purpose, TRNSYS [25] has been exploited since its radiation data module considers inter-reflections between buildings, based on Gebhart factors formulation [26,27], when a "false" zone method is adopted. Gebhart formulation allows to calculate the shortwave solar loads on the surfaces of a semi-enclosed space, considering the effect of multiple diffusive inter-reflections between them. More specifically, by modelling the street canyon as an interior thermal zone, TRNSYS applies the detailed radiation module calculating the multiple reflections both in the shortwave both in the longwave field.

An urban canyon with three different aspect ratios was chosen (H/W = 0.5, 1 and 2), with two different orientations (N-S and W-E), with two transparent/opaque surfaces ratios (A_{gl}/A_{op} = 0.5 and 0.25) and 4 values (0.2, 0.4, 0.6, 0.8) of solar absorption factor of the envelope surfaces. The peaks and the mean values of absorbed solar radiation on the external walls of the street canyon building were evaluated, such as the seasonal absorbed radiation. Finally, the influence on building thermal energy demands of multiple shortwave inter-reflections was evaluated comparing the results with a reference case with no inter-reflections.

The results of study may contribute to quantify, by means of corrective factors, the contribution of the shortwave inter-reflections in the thermal energy consumptions predicted by BES tools that accounts only of shadowing factors. Considering that increases in cooling demand up to 35% were found, our numerical model underlines the importance of considering the multiple reflections inside urban environment for an accurate evaluation of thermal energy demands of buildings inserted in their actual context. For these reasons, in planning phase, urban designers may consider the importance of the effects of multiple inter-reflections to adopt passive solutions to optimize the outdoor environment, such as smart materials or urban configuration. The details about the conditions imposed for the numerical model in this work to account only of the shortwave multiple reflections are reported in Section 2.

2. Methodology

In this paper, the dependence on the shortwave multiple reflections as a function of different parameters of space heating and cooling demands of a three-floor building for residential use was analyzed. A study on shortwave radiation fluxes on the building façades and on envelope opaque has been carried out. Simulations were performed for a building considered in an urban context, adjacent on both main long sides to street canyons. The BES software used to perform the numerical simulations in this work is TRNSYS 17.0, a transient 3D multi-zone building code able to simulate dynamically the energy behavior of a building with time steps of less than one hour.

2.1. Numerical model

The heat flow by conduction through the envelope components is modeled by means of 1D transfer functions. For what concerns the convection mechanism on the envelope surfaces, TRNSYS gives the possibility to set outside and inside convective heat transfer coefficient (CHTC). In this paper, wind speed depending values of external CHTC are adopted following the current standard [28] while for internal CHTC constant values were chosen. In TRNSYS radiative heat flows are modeled differently for outside and inside surfaces. More specifically, solar irradiation on envelope elements is considered as a gain while the longwave radiation is treated as a heat loss to the cold sky. A radiation model which account of the multiple reflections is provided only for interior thermal zones. This fact implies that, in case of a street canyon building modeled as an outdoor environment, the radiative model does not consider either the shortwave or the longwave inter-reflections between the façades of street canyon buildings. Since the final purpose of this work is to investigate the influence of radiative trapping effect of the street canyon environment on the energy demand of a building, the space between the buildings was modeled as an interior thermal "false" zone with virtual border roof and walls.

For what concerns the features of the studied building, the length is 110.5 m, since one of the purposes was to represent a long building with similar adjacent apartments but also to minimize the effects of the boundary conditions on the short sides of the building. Both the height and the width of the building are 13.5 m. The short side walls are modeled adiabatic assuming they are continuous, thus modeling a long row of identical thermal zones. The street canyon building under analysis is surrounded by two other rows of buildings, geometrically identical to the studied building (Fig. 1). More details of the numerical model are reported in a previous work where a validation process has been performed [29].

Since the objective of the study is the evaluation of the influence only of the shortwave multiple reflections on thermal energy demand of building, the longwave exchange phenomena had to be inactivated: it was necessary to set emissivity equal to 0. As a matter of fact, the shortwave radiation (both directly absorbed and absorbed by multiple reflections) contributes, in the thermal energy budget, to increase the surfaces' temperatures. Hence, the multiple reflection in the longwave field is dependent from shortwave radiation budget. Again, the space cooling and space heating energy demands is a function of envelope surfaces' temperatures too, that is influenced also by longwave radiation exchange (aside from convection and conduction).

Therefore, it is clear it was necessary to hide the influence of longwave radiation exchange on the building thermal energy demand. This approach is necessary since the final purpose of the work is the evaluation of the impact of only shortwave multiple inter-reflections on building thermal energy demands. By setting the model in this way, the longwave radiation losses to sky and to