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Impact of urban microclimate on summertime building cooling demand: A parametric analysis for Antwerp, Belgium

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HIGHLIGHTS

- One rural and two urban microclimatic conditions are specified with CFD simulations.
- The urban locations are positioned 80 m and 400 m away from a park.
- BES are performed considering buildings with varying characteristics and use types.
- The effect of urban microclimate is studied based on monthly Cooling Demand (CD)
- Buildings near the park have 13.9% less CD than the buildings away from the park.

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ABSTRACT

Meteorological measurements are conducted in Antwerp, Belgium in July 2013, followed by CFD urban microclimate simulations considering the same city and time period. The simulations are found to be able to reproduce measured air temperatures inside central Antwerp with an average absolute difference of 0.88 °C. The simulation results supplemented with measurements are used to generate location-specific Microclimatic Conditions (MCs) in three locations: (1) a rural location outside Antwerp; (2) an urban location inside Antwerp, away from an urban park; and (3) another urban location, close to the same park. Building Energy Simulations (BES) are performed for 36 cases based on three different MCs, two building use types and six sets of construction characteristics, ranging from pre-1946 buildings to new, low-energy buildings. Monthly Cooling Demands (CDs) are extracted for each case and compared with each other. The results demonstrate that compared to the air temperatures in the rural area, on average, air temperatures at the urban sites away and close to the park are 3.3 °C and 2.4 °C higher, respectively. This leads to an additional monthly CD of up to 90%. CDs of buildings with better thermal insulation and lower infiltration rates can increase by 48% once moved from the rural location to an urban location, which may lead to the reconsideration of design guidelines of low-energy buildings exposed to an urban MC. Although the proximity of an urban park cannot fully compensate the increased CD by an urban MC, residential buildings close to the park are found to have on average 13.9% less CD during July 2013, compared with buildings away from the same park. The influence of the urban park on the CDs of buildings in its vicinity is strongly linked to the meteorological wind direction. Professionals focusing on energy-efficient buildings in cities are advised to conduct energy predictions with location-specific MC data, instead of only using city-averaged meteorological data.

1. Introduction

According to the European Commission and the United States (US) Energy Information Administration, buildings are responsible for approximately 40% of the total energy demand in the European Union (EU) and the US [1,2]. Among the energy used in buildings within the EU, space heating has the largest share, but with the new building regulations that demand well-insulated building envelopes, the share of space heating is expected to decrease in the future [3,4]. In contrast, space cooling has a lower share among the total building energy

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demand but due to climate change [5–7], heat waves [8–11] and rapid urbanization [12,13], the share of space cooling is expected to rise [4,14]. Building energy demand can be affected by different aspects on different scales, such as occupant behavior [15,16], building installations [17,18], building envelopes [19–21] and urban microclimate [22–24].

Urban microclimate can be defined as the local climate observed in urban areas, which can be significantly different from the climate of surrounding rural areas [25]. With the rapid urbanization of the world population [26,27], research on urban microclimate has gained popularity in the past years [22,28,29]. From the building energy perspective, urban microclimate can be considered as the set of meteorological conditions to which buildings in cities are subjected. The effect of urban microclimate on building energy demand is mostly researched within the theme "Urban Heat Island (UHI) effect" [30–33]. Studies on the topic typically follow two steps: (1) Analysis of urban microclimate with specific target microclimate parameter(s) (mostly air temperature); (2) and then calculating building energy demand, mostly with Building Energy Simulations (BES) [34,35] while using target microclimatic parameter(s) as an input.

For the urban microclimate part, the majority of the studies in the literature collected measurement data from different parts of the same urban area [12,30,31,33–42]. The collected data were subsequently used to define a series of location-specific Microclimatic Conditions (MCs). Measurement studies typically focus only on air temperature as the target microclimate parameter, which can be considered reasonable as several statistical studies, such as Sailor and Munoz [43] and Fung et al. [44], demonstrated that deviations in air temperature are responsible for almost all the deviations in building energy demand.

Urban microclimate can be investigated also with computational approaches. The main advantage of computational approaches over measurements is the ability to generate spatially explicit information for the target microclimatic parameters [45,46]. In addition, a proven and appropriate computational methodology for urban microclimate analysis can be used to investigate different urban design scenarios, which would be very challenging to investigate with measurement campaigns [47–49]. In Table 1, an overview of studies investigating the effect of urban microclimate on building energy demand with a computational approach on urban microclimate analysis is provided. The following entries are used: authors and publication year; computational methodology; microclimate cases; target parameter(s); building types investigated.

Some studies in Table 1 used data morphing techniques, which refers to the addition of pre-measured UHI intensities (°C) (UHI scenarios) to the measured rural air temperatures [50,51]. Several studies used UHI predictor tools such as the Urban Weather Generator [52], which predicts the UHI intensity (°C) based on location-specific morphological parameters (i.e. canyon aspect ratio) [53–57]. Kolokotroni et al. [58] used an artificial neural network model to predict urban microclimatic parameters. Another methodology for urban microclimate analysis is Energy Balance Models (EBM) [59], which are employed in several studies [60–64]. Some studies performed Computational Fluid Dynamics (CFD) simulations to analyze urban microclimate [65–67] whereas others employed a coupled CFD-EBM approach [68–71]. CFD analysis of urban microclimate is a developing research field [29,46,49] and the coupling of velocity and temperature fields with a high spatial resolution is an advantage over other computational approaches [45]. However, CFD simulations can be computationally demanding [45,46,68].

In Table 1, the table entry "(micro)climate cases" lists the different (micro)climatic conditions each study has evaluated, such as urban vs. rural climates. The entry "target parameters" lists the calculated microclimatic parameters that are used as input for calculating building energy demand. The entry "Building types" denotes whether different building types were considered within the same study. Compared with previous studies, the present study provides two clear distinctions.

The first distinction concerns the compared microclimate cases. To the best of our knowledge, no prior study on the topic considered the impact of meteorological wind direction on the energy demand of different buildings in the same urban area, which can be influential [34,72]. The measurement study by Ca et al. [34] demonstrated that in the presence of a local cooling source (e.g. an urban park), buildings in the same urban area can have varying energy demands, depending on their locations with respect to the prevailing wind direction. To investigate this, in addition to a typical rural vs urban microclimate comparison, the present study considers an urban-urban comparison where one of the target buildings is chosen close to an urban park and the other is chosen away from the same urban park.

The second distinction concerns the uncertainties related to the building under study. The hypothesis of this paper is that the effect of urban microclimate on building energy demand can vary significantly for buildings with different construction characteristics (e.g. U-values of the construction components) and with different use types (e.g. residential vs office buildings). Even though some previous studies focused on similar considerations [35,54,55,67,71,73,74], the aim of this paper is to demonstrate this complexity by focusing on a wider group of buildings ranging from pre-1946 buildings to modern low-energy buildings and to challenge the common considerations on energy efficient building design.

In this study, CFD urban microclimate simulations are performed for the Antwerp central region and the resulting air temperatures are compared with measurement data obtained during July 2013. Measurement data and CFD simulation results for air temperature (°C), wind speed (m/s) and wind direction (°) are extracted at three locations: (1) a rural area outside of Antwerp; (2) an urban area inside central Antwerp, away from an urban park and (3) another urban area inside central Antwerp, close to the same urban park. Based on the CFD simulation results, three location-specific MCs are defined. The resulting MCs are used as input for the building energy simulations (BES) of a building with the same form and orientation but with different use types and with different construction characteristics. The resulting building cooling demands are reported for every individual case and compared with each other.

2. Description of the study area, buildings and measurement campaign

This study focuses on Antwerp, a city located in the North of Belgium (Fig. 1a). The area of interest in this study is the central Antwerp area (Fig. 1b), specifically the area surrounding the urban park named "Stadspark" (Fig. 1c). Municipal drawings and the GIS database corresponding to the area of interest are acquired from the city of Antwerp GIS service. The data contains the locations of all the buildings and the trees taller than 2 m. 365 buildings are specified in the area of interest and in Fig. 2a, the height distribution of these buildings is provided. The highest building is 60 m and the buildings within the 9–11 m height interval are the most common (75/365, or 21%). The average building height in the area of interest is 13 m. The Entranze database [75] reports the distribution of the buildings in Belgium with respect to their construction dates. This distribution is demonstrated in Fig. 2b, which shows that the majority of the buildings in Belgium are constructed prior to 1970 (62% of all buildings). Note that the data on Fig. 2b do not pertain to the study area itself but to all the buildings in Belgium.

Meteorological measurement data used in this study is collected by the Flemish Institute for Technological Research (VITO) [76]. The measurements were conducted by stations at two locations: (1) On the rooftop of a high-school building in central Antwerp (Fig. 1c); and (2) in a rural area located 8 km away from the central Antwerp area (Fig. 1b). The urban measurement station was positioned 2 m above the approximately 5 m high building rooftop (approximately at 7 m height from the ground level) and the rural measurement station was