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Influence of building surface solar irradiance on environmental temperatures in urban neighborhoods

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ABSTRACT

For buildings located in actual urban neighborhoods, modeling of outdoor airflow with Computational Fluid Dynamics (CFD) requires solar radiation at building surfaces to predict local environmental temperatures. This study conducts a parametric analysis to support the development of coupled simulations of outdoor airflow and solar radiation simulations at building surfaces. To account for different assumptions used in the outdoor modeling, this study uses OpenFOAM CFD and couples it with three different simulation engines, including EnergyPlus, Daysim, and Radiance to predict simulated outdoor solar irradiance for implementation in outdoor CFD simulations. The primary aim of selecting these three simulation engines is to evaluate tradeoffs between the model complexity and accuracy for simulated outdoor solar irradiance for outdoor CFD simulations. Examined parameters include: (i) surface representation with different mesh types, (ii) urban plan area density, and (iii) the impact of simulated solar irradiances on the simulated air temperature and velocity values in the CFD simulations. The study results showed that the surface representation has up to a 7.6% and 133% influence on the simulated outdoor global and local solar irradiances, respectively. The surface thermal boundary conditions have up to 1.5 °C difference on the air temperature and negligible impacts on the air velocity.

1. Introduction

Land coverage and distribution of the impervious and pervious surfaces changes the rate of heat transfer processes in the built environment. Existence of impervious surface material properties lead to higher levels of heat storage in the total energy budget of urban neighborhoods, and alter the rate of sensible and latent heat transfer rates. For example, impervious exterior surface of buildings can reach high temperature values on sunny days, and this heat is then convected and radiated into the surrounding air and surfaces (Lu & Weng, 2006). At the large city scale, this phenomenon results in the Urban Heat Island (UHI) effect, which refers to the higher temperatures present in dense urban areas when compared to surrounding rural and suburban regions (Mirzaei, 2015; Touchaei & Wang, 2015). Many existing studies focus on energy balances of large city areas for the UHI effect, while a few studies examine local temperatures and microclimate (Gracik, Heidarinejad, Liu, & Srebric, 2015; Srebric, Heidarinejad, & Liu, 2015). This study focuses on the urban neighborhood scale to allow modeling of the solar irradiance on the building surfaces and consider the influence of the local urban microclimate on the airflow around a building using Computational Fluid Dynamics (CFD) simulations. Specifically, CFD modeling combined with solar irradiance modeling of building surfaces enables accounting the influence of surface radiative properties on the local air temperatures around buildings in urban neighborhoods. This study uses open-source software packages including, EnergyPlus, Radiance, and Daysim, to calculate heat fluxes at the building surfaces and to implement these heat fluxes in the outdoor CFD simulations with OpenFOAM solver. This approach allows prediction of local air temperatures dependent on building surface material properties in the context of an urban neighborhood.

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The combined airflow and solar irradiance modeling on the building surfaces at the urban neighborhood scale requires solving systems of partial differential equations. Three different methods, including analytical, experimental, and numerical could solve this system of equations. Analytical modeling involves the direct solution method using assumptions to reduce the system of equations to a closed form. Since this is only possible on simple geometries, it is not a useful technique for solving the combined outdoor airflow and solar irradiance in actual urban neighborhoods. Experimental and numerical modeling methods allow solutions of this equation system representing actual neighborhoods. Experimental methods entail wind tunnel measurements or placement of sensors in the urban environment to measure air temperature, wind velocity, and solar intensity among other variables (Shahrestani, Yao, & Cook, 2013; Srebric et al., 2015). The experimental methods accurately represent local temperatures and wind speeds, but the measurements are limited to areas covered by the sensors. Initial and calibration costs as well as accuracy of the sensors are another limiting factor in the experimental method. Due to these limitations, the numerical simulation method is an attractive technique for resolving the temperature and velocity fields in urban areas (Ashie, Thanh Ca, & Asaeda, 1999; Mirzaei & Haghighat, 2010). Nevertheless, the experimental method, such as the wind tunnel or in-situ experiments, is valuable in validating results from a numerical model (Defraeye, Blocken, & Carmeliet, 2010). Overall, among the three methods, numerical method can offer insights for the early design stage of buildings because it allows a parametric study of the inputs, and provide performance predictions of buildings and urban neighborhoods. Therefore, this study uses the numerical method to calculate building exterior surface heat fluxes as thermal boundary conditions for the outdoor airflow CFD simulations.

Building design practice is gradually moving toward using integrated simulation tools to perform simulations for airflow, radiation, daylight, and building energy consumption of the buildings and perform parametric analysis for building sustainable urban neighborhoods (Stavrakakis et al., 2012; Taleb & Musleh, 2015). However, there is a need for additional inputs from the building industry and building research community to support and increase the market share of this integrated simulation approach. In practice, building performance predictions use airflow, radiation, daylight, and building energy consumption separately. However, these heat and mass transfer processes are not separated from each other, meaning there is a need to include coupled simulations to enable better design of buildings. This integration of tools will support the design of green buildings and sustainable cities (Fan, Borong, & Peng, 2013). Use of simulation tools to design buildings does not necessarily lead to better representation of actual heat and mass transfer processes of the building performance or faster building design. Without consideration of the design need, each simulation tool could overconsume the computational and human resources. As an example, a complete integration of an outdoor solar radiation simulation with a CFD simulation for a neighborhood requires a substantial amount of resources and may not lead to accurate simulation results. Limitation and benefits of using different tools to calculate outdoor solar radiation on the building surfaces is an important input for the outdoor airflow CFD simulations. This input allows a better representation of heat fluxes or exterior building surface temperatures for the CFD simulations. Therefore, this study conducts a parametric analysis to elaborate:

[(4)]

(1) Use of EnergyPlus, Radiance, and Daysim to calculate outdoor solar radiation on the building surfaces for using in the outdoor airflow CFD simulations.
(2) Impacts of using different assumptions to represent the surfaces for buildings located in urban neighborhoods.
(3) Benefits and limitation of utilizing simulated solar irradiances for implementation in the airflow simulations.
(4) Quantifying influence of different solar irradiance simulation tools on the airflow temperature and velocity variations.

2. Combined airflow and solar irradiance modeling

This study reviewed outdoor airflow simulations around buildings located in urban neighborhoods, and the implication of using different thermal boundary conditions for the outdoor airflow CFD simulations. A labor-intensive approach uses the on-site measurements to implement the surface temperature readings as boundary conditions for the airflow CFD simulations (Fintikakis et al., 2011). In the design of sustainable urban neighborhoods, this approach would require significant number of measurement data points. Therefore, the present study focuses on irradiance simulations as an alternative source of thermal boundary conditions for outdoor CFD simulations of urban neighborhoods that could provide opportunities to design more sustainable neighborhoods.

2.1. Outdoor airflow simulations

Previous outdoor airflow CFD studies at the microscale analyzed design in the urban environment such as: (1) examination of outdoor thermal comfort, (2) assessment of urban heat island, and (3) calculation of outdoor local temperature. CFD has been used to examine outdoor thermal comfort (Huang, Ooka, & Kato, 2005; Mochida & Lun, 2008), pollutant dispersion (Baik, Park, & Kim, 2009; Xie, Huang, Wang, & Xie, 2005), greenspace effect on urban heat islands (Ashie et al., 1999; Takahashi, Yoshida, Tanaka, Aotake, & Wang, 2004), local temperature effect on Coefficient of Performance (COP) (Chow, Lin, & Wang, 2000; Gracik et al., 2015), and effect of urban density on outdoor Convective Heat Transfer Coefficient (CHTC) (Liu, Heidarinejad, Gracik, & Srebric, 2015; Liu, Srebric, & Yu, 2013). Many microscale studies adhere to similar simulation setup standards, and several institutions have compiled their own set of standards, such as the Architectural Institute of Japan (Tominaga et al., 2008) which heavily references results of a European COST (Cooperation in Science and Technology) 732 Action Network (Franke, Hellsten, Schlünzen, & Carissimo, 2007). In terms of the implementation of the thermal condition on the exterior surfaces, most of the existing simulations relied on the radiation modules available in the commercial CFD software packages such as Solar Position and Intensity Code (Solpos) implemented in Fluent or IMMERSOL in PHOENICS (Liu, Heidarinejad, Gracik, Srebric, & Yu, 2015; Stavrakakis et al., 2012; Taleb & Musleh, 2015). Other simulations used simplified urban neighborhood configurations in the urban scale representation of neighborhoods, such as the urban canopy models (Touchaei & Wang, 2015), allowing these studies to benefit from the existing urban morphology parameters. Therefore, based on the conducted literature review, the current study uses the simplified urban neighborhoods used in the literature as case studies to represent the urban neighborhoods. The selected case studies in this study include different urban neighborhood morphologies.

2.2. Thermal boundary conditions for outdoor airflow simulations

Boundary condition for building surfaces in the urban neighborhood is a crucial aspect of modeling airflow around the buildings. Thermal boundary conditions in the urban neighborhoods are constantly changing due to dynamic occurrence of the heat transfer processes, meaning a simple steady state solution may not accurately represent the thermal boundary condition. Thermal mass of the building material is another large factor in determining the heat flux from the building. Previous urban studies encompass a