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Effect of urban neighborhoods on the performance of building cooling systems

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ABSTRACT

This paper quantified the influence of the urban neighborhood on the degradation of Coefficient of Performance (COP) for the building cooling systems. Urban microclimate usually creates higher air temperatures in dense urban areas compared to surrounding rural and suburban regions. Computational Fluid Dynamics (CFD) combined with building energy simulations can predict local hourly temperatures in urban environments. This study uses open source software packages, including OpenFOAM and EnergyPlus, to calculate local air temperatures and heat fluxes on the building surfaces as well as resultant operational COP values. First, the simulated temperature calculations of local airflow temperatures are indirectly validated using on-site field measurements in an actual urban neighborhood. Further, the validated CFD simulations predicted local air temperatures in uniform neighborhoods of varying density. This study identified four types of COP equations to quantify performance of cooling systems as a function of outdoor air temperatures. The study findings indicate that for the present study's climate and flow conditions, rooftop air conditioners in urban areas can have a reduction in COP up to 17%, compared to COP in a corresponding rural area. Window air conditioners can have reductions in COP of over 16%, if located on the windward walls. However, this average COP degradation for the cooling systems installed on the leeward walls is not significant. Overall, the effect of neighborhoods on the performance of cooling systems is significant and quantifiable, and this quantification requires consideration of the common local design practices for the installation of building cooling systems.

1. Introduction

The rapidly urbanizing world is causing drastic changes to global energy use patterns. At the beginning of the 20th century, 13 percent of the world's population lived in urban areas. Today, over 50 percent reside in urban areas [1]. This continued urbanization is exasperating the Urban Heat Island (UHI) effect, which affects the microclimate of cities. The UHI effect is partially due to the thermal properties of common building materials and heat transfer among building surfaces in the built environment [2]. For example, the building materials with high solar energy absorption cause high surface temperatures leading to warming of the surrounding air. This increase in the local air temperatures due to UHI exacerbates the existing demand to cool buildings. Therefore, there is a need to quantify the additional demand on cooling equipment capacity due to the increase in the surrounding local air temperature and ultimately degradation in the efficiency of the building cooling systems.

Numerous studies have considered different aspects of the urban neighborhood influence and ultimately UHI on energy consumption of the buildings and the implication of the changes in the local thermo-fluid properties on the modeling of the buildings. For example, existing studies explored the influence of the UHI on the cooling demand of the buildings [3,4], energy consumption of the buildings [3,5,6], local temperature increase [7,8], air velocity variations [9], Convective Heat Transfer Coefficients (CHTCs) [10–12], as well as short- and long-wave solar radiation [13,14]. However, these existing studies did not examine the impacts of the UHI and urban neighborhood on the performance degradation of the Heating, Ventilating and Air-Conditionings (HVAC) systems.

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Therefore, this study considers the impacts of the local urban neighborhood on the thermo-fluid properties of the airflow and temperature fields and their implications on the degradation of the cooling system efficiencies.

In actual buildings, efficiency of the HVAC systems directly depends on outdoor air temperature with the increase in local temperatures resulting in the decrease of building HVAC systems efficiency. For the theoretical reverse cycle, Carnot efficiency shows that the Carnot cycle's efficiency decreases with increasing the hot reservoir temperature. Previous studies have emphasized the diurnal changes in the Coefficient of Performance (COP) of the HVAC system [15,16]. However, these studies did not fully examine the link between the impacts of the urban neighborhood on the local air temperature and corresponding degradation of the cooling systems. Computational Fluid Dynamics (CFD) is a reliable tool to calculate the local spatial and temporal temperatures in urban environments that requires previous backgrounds in the outdoor simulations [17,18]. Therefore, this study utilizes CFD to predict the flow field around the building of interest and calculate the diurnal changes in the COP of HVAC systems due to the local urban neighborhood characteristics.

Several existing CFD studies calculated local temperatures, and these studies used a variety of methods to define appropriate thermal boundary conditions [19–21]. A few studies have also applied CFD to estimate the local temperatures and corresponding COP of HVAC systems [22–26]. These COP studies focused on the temperature stratification for high-rise buildings, rather than the elevated temperatures due to urban density. Therefore, this study aims to utilize the existing empirical COP equations with validated building airflow and energy simulation models to quantify changes in the COP of cooling systems.

In the interest of making the research results accessible to a large audience of users, it is advantageous to use open source simulation software. The performance of OpenFOAM open source CFD software has been shown to be capable of providing validated results for isothermal urban environments [27]. This study provides an indirect validation of the OpenFOAM simulation results in non-isothermal environments with on-site field measured data to assess the accuracy of predicted local temperatures for an actual urban neighborhood with urban plan area density of 0.25. Urban plan area density (λ_p) is the ratio of the built area projected onto the ground surface divided by the total land area under consideration. In addition, this study developed an open source simulation framework using OpenFOAM and EnergyPlus to calculate local temperatures in urban neighborhoods. A comparison between CFD and measured temperature data collected at the Penn State campus served as a validation study for the developed framework. This study benefited from a validation method that was previously published to indirectly validate the outdoor CFD simulation results [12]. Finally, the developed CFD simulations for neighborhoods with varying plan area densities enabled calculations of the change in COP for highly dense urban neighborhoods.

Overall, the reduction in efficiency of cooling systems due to urban density is an important parameter when considering future infrastructure investments for urban neighborhoods. This study assesses the degradation of COP while it considers the following criteria:

(1) Make consistent decision-making regarding CFD case study setup for urban neighborhoods using systematic consideration of the boundary conditions, mesh generation, and inputs.
(2) Deploy open source software for simulations, including OpenFOAM for the CFD simulations, EnergyPlus for the building energy simulations, and ParaView for the visualization of the outputs.
(3) Establish best practices for handling the thermal boundary conditions of urban neighborhoods based on validation of the CFD simulations with the on-site measured data.
(4) Quantify the effect of urban density on the efficiency of cooling systems due to local thermal conditions by utilizing the existing COP equations for actual operating conditions of HVAC systems.

2. Research methodology

The research methodology includes details about the modeling procedure and inputs for CFD and energy simulations to evaluate the impacts of the urban neighborhood on the performance of the HVAC systems [28].

2.1. Modeling procedure

This study used CFD and building energy simulations to develop a framework, enabling evaluation of the influence of the urban neighborhood on building cooling systems. Fig. 1 illustrates the developed framework in this study. First, this study assessed the effectiveness of the proposed framework with the validation of the simulation results for an actual urban neighborhood in a non-isothermal environment. Then, this study extended the applicability of the framework to hypothetical buildings located in six different urban neighborhood densities. This framework used the open source packages to perform the simulations, EnergyPlus and OpenFOAM. Any simulation engines or models with proprietary access are not included in this study. The airflow simulations with OpenFOAM have validation for isothermal conditions in urban neighborhoods [27]. The building energy simulations with EnergyPlus provide validated thermal behavior of the building envelope and its HVAC systems throughout a year [29]. Simulation results from EnergyPlus supplied OpenFOAM with building surface temperatures/fluxes as the boundary conditions, while CFD simulations provided convective heat transfer into the atmosphere at external building surfaces [11]. SketchUp with the OpenStudio plugin produced building geometry in the STL (STereoLithography) format for OpenFOAM, as well as the IDF (Input Dictionary File) format for EnergyPlus. To simplify the computational framework, the building energy and CFD simulations ran in parallel with hourly exchange of data from EnergyPlus to OpenFOAM.

2.2. Description of the selected urban neighborhoods

The validation study uses an actual urban neighborhood with measured data for four buildings located at Penn State's campus neighborhood. The buildings are 10 stories tall, and measure 20 m × 30 m × 28 m. The short surfaces of the buildings have a Window-to-Wall (WWR) ratio of 0.15, and the long surface WWR is 0.2. The actual urban neighborhood has a plan area density of 0.25. Due to the existence of low WWR for the selected buildings, this study used the existing methods in EnergyPlus to calculate the solar radiation that encompasses both long-wave and short-wave radiation. The further study included neighborhoods with six different plan area densities, 0.04, 0.063, 0.11, 0.16, 0.25, and 0.44, corresponding to a building spacing ranging from 5 m to 40 m. These urban densities represent sparse rural/suburb areas ($\lambda_p = 0.04$) up to dense city centers ($\lambda_p = 0.44$). Fig. 2 illustrates two different plan area densities and position of the building of interest in the center. Previous roughness studies established that flow fields over arrays of cubes experience three different airflow regimes [30]. In the lowest density arrays, each cube is largely isolated from the effects of the other cubes. In the middle density