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Different modeling strategies of infiltration rates for an office building to improve accuracy of building energy simulations

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ABSTRACT

Air infiltration rates directly impact building energy consumption to a larger or smaller degree depending on the tightness of building enclosure and heating ventilation and air conditioning system operation. The relative importance of infiltration airflows has been increasing in total building energy consumption due to the improvements in building insulation and window products. The objective of this study is to compare the accuracy of building energy simulations associated with different air infiltration rates calculation approaches. This study used different sources of infiltration rate: time-dependent simulated data, AIVC database, and default settings in building energy simulations. A coupled framework associated with time-dependent infiltration rates is used by integrating computational fluid dynamics and multi-zone airflow modeling results into energy simulations. This framework is demonstrated with a case study for an office building in Michigan. The case study also uses the infiltration rates obtained from the database and default settings in energy simulation program. The comparison between simulation results and utility data shows that time-dependent infiltration rates could increase the accuracy of energy simulations with 3–11% reduction in the coefficient of variation of the root mean square error (CVRMSE), and 2–11% reduction in the normalized mean bias error (NMBE).

1. Introduction

Air infiltration is the unintentional airflow into a building through different openings in building enclosure. Infiltration rates can have a significant effect on the building energy consumption [1,2]. In a study conducted during 1980s, the energy loss due to infiltration was estimated to be between 6% and 9% of the total energy budget for the US [3]. The relative importance of infiltration airflows has been increasing in the total building energy consumption due to the improvements of building insulation and window products. Another more recent study shows that infiltration is responsible for approximately 13% of the heating loads and 3% of the cooling loads for the US office buildings. Specifically, for newer buildings, infiltration is responsible for about 25% of the heating loads and 4% of the cooling loads due to the higher levels of insulation [4]. The problem is worldwide, for example, according to a study in 2009, infiltration causes about 15–30% of the energy use for space heating including ventilation in a typical Finnish detached house. In this case, the average infiltration rate and heat energy use was increasing almost linearly with the building leakage rate [5].

The air infiltration rates in buildings are driven by the pressure difference across the building envelope caused by wind and air density differences due to temperature differences between inside and outside air. Mechanical systems also contribute to pressure differences across the envelope. The indoor/outdoor pressure difference at a location depends on these driving mechanisms as well as on the characteristics of the openings in the building envelope.

The actual wind pressure distribution profile, as one of the important infiltration driving mechanisms, depends on the wind direction, wind speed, air density, surrounding terrain, and building layout. The data sources of wind pressure coefficients (C_p) are classified as primary and secondary sources. The primary sources include full-scale measurements, reduced-scale measurements in wind tunnels and computational fluid dynamics (CFD), while the secondary sources of wind pressure coefficients mainly include databases and analytical models. A study provided an overview of different pressure coefficient data in building energy simulation and airflow network programs [6]. The overview shows that

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the pressure coefficients from different data sources show large variations when applied to the same building.

The building construction quality is another significant factor influencing building infiltration rates. The accuracy of infiltration rate calculations directly depends on the construction quality represented as the building leakage areas. Ideally, the size, location and characteristics of all leakage areas should be known. However, these properties are difficult to quantify. Besides, the uncertainty of building leakage areas could be greatly increased by different manufacturing and installation processes [7].

Currently, available methods for evaluating the building air leakage area and associated infiltration rates range from simple air change methods to complex physical modeling methods. The previous studies have been using different sources of the infiltration rates in building performance simulation. Infiltration rates could be set up as certain air change rates according to an estimation of building envelope tightness [8] [9]. Infiltration rates could also be calculated according to numerical equations [10] and correlations with wind speed [11]. Multi-zone modeling simulation is employed in building performance analyses to consider building detailed configurations and provide relatively accurate infiltration rates [4]. In building energy simulation tools, such as EnergyPlus, the calculation methods of infiltration rates typically use default infiltration rates depending on different leakage properties of the buildings such as: leaky, normal, and tight. These three categories of building leakage do not account for the infiltration driving mechanisms and other building characteristics. Consequently, the assumed infiltration rates in EnergyPlus do not reflect the direct impacts of outdoor weather conditions [12]. Therefore, the default settings for infiltrate rates do not directly reflect the actual infiltration rates in building energy simulations. However, to the authors' knowledge, there has been no study analyzing the uncertainty of building performance simulation correlated with different infiltration rates calculation methods.

To more directly reflect the actual weather conditions, a study by the Pacific Northwest National Laboratory (PNNL) proposed a simplified approach to account for wind-driven infiltration rates into buildings [13]. The method uses an average wind speed coefficient for a square office building to calculate a base infiltration rate that is further varied with the incoming average wind speed using a capability within EnergyPlus. Even though this approach addresses wind-driven infiltration, it is not accounting for the infiltration rates due to the stack effect. Furthermore, another research study on airflow rate calculations indicated that the underestimation and overestimation due to surface-averaged pressure coefficients are not negligible [14]. Therefore, the simplified methods may not be sufficiently accurate for energy simulation tools required to satisfy high accuracy levels as defined by ASHRAE guideline 14-2002 [15].

Among the physical modeling methods, a recent research study developed a roadmap for performing full 3-D envelope simulations to calculate air leakage in buildings [16]. This physical modeling method realistically depicts the various cracks common in an envelope in terms of shape, location, and quantity, so it is very computationally demanding. Another group of models focuses on better representation of specific building enclosure elements know to make significant impact on the total building infiltration rates, such as windows [17], doors with air curtains [18], and revolving doors [19]. However, the existing studies do not focus on comparing the influence of different infiltration rate calculation methods on the accuracy of building energy simulation results for commercial buildings.

Overall, there have been many different calculation strategies of infiltration rates in both theoretical and practical studies. Therefore, it is important to understand the accuracy level of building performance analysis associated with different methods of infiltration rate calculations. The purpose of the present study is to compare the impact of infiltration rates from different data sources on the accuracy of building energy simulations, and discuss the uncertainty of simulated energy consumption associated with the infiltration rates.

2. Methodology

The methodology focuses on the wind pressure coefficients and building leakage areas because the heating ventilation and air conditioning (HVAC) imposed pressures are predefined by the building design/operation already accounted in energy simulations, while the wind pressures depend on the weather and surroundings.

The major data sources of wind pressure coefficient (C_p) include measurements [20], computational fluid dynamics (CFD) simulations [21], databases and analytical models [22]. Measurements include full-scale measurements and reduced-scale measurements in wind tunnels. Generally, measurements are complex, time-consuming and expensive. Both full-scale and wind-tunnel measurements are limited by high equipment costs, intense labor, and demanding time requirement for data collection [6]. Therefore, the present study focuses on comparing energy simulation accuracy resulting from infiltration calculations using wind pressure coefficients (C_p) from CFD modeling and Air Infiltration and Ventilation Centre (AIVC) database as relatively inexpensive data sources when compared to measurements as a data source.

CFD has been employed to study airflow and contaminant dispersion around and in buildings for a few decades [23–25]. More recently, CFD is also used to simulate the wind pressure on building envelope [26–28]. CFD is able to consider all major factors in development of pressure coefficients, including local wind profile, building orientation and shape, terrain and sheltering effects of surrounding buildings [29]. A popular tool that uses these pressure coefficients to calculate infiltration rates is multi-zone modeling based on a simplified macro-representation of the bulk airflow in and around a building [30]. The advantages of multi-zone modeling are simple problem definition, straight forward representation, and clear calculation procedure. However, due to the perfect-mixing assumption of air in each zone, multi-zone modeling is not able to provide detailed temperature, airflow and pressure distributions within a single space [31]. Therefore, an integration of the airflow multi-zone modeling and CFD methods provides a balance between complementary information on building physics and required simulation resources. As a result, the combination of CFD and multi-zone models has been investigated and applied in several studies [32].

The building energy simulation framework accounting for infiltration rates by integrating CFD and multi-zone modeling is shown in Fig. 1.

CFD provides detailed model to simulation airflow pattern around the building and also provides wind pressure distribution profile. A multi-zone model uses this wind pressure distribution profile and building leakage area as inputs. The output of the multi-zone modeling, infiltration rates, together with the weather files and building thermal properties, are important inputs to building energy simulation. EnergyPlus is employed as building energy simulation tool in this framework due to its capability to modify every detailed parameter in open source architecture.

Besides the coupled CFD/multi-zone modeling approach, databases are also employed as an alternative data source of wind pressure coefficients (C_p). The two widely used databases often found in the ventilation and infiltration literature include the AIVC database [33] and ASHRAE database [34].