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Optimizing the thermal performance of building envelopes for energy saving in underground office buildings in various climates of China

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ABSTRACT

This article investigates the influence of the thermal performance of building envelopes on annual energy consumption in a ground-buried office building by means of the DeST-based dynamic building energy simulation, aiming at offering reasonable guidelines for the energy efficient design of the envelopes of underground office buildings for various climatic zones in China. In this study, the accuracy of dealing with the thermal process adopted for underground buildings by using DeST is validated by measured data. The analysed results show that the annual energy consumptions for this type of buildings vary significantly, and it is based on the value of the overall heat transfer coefficient (U-value) of the envelopes. Thus, it is necessary to optimize the U-value for underground office buildings located in various climatic zones in China. With respect to the roof, an improvement in its thermal performance is significantly beneficial to the building in terms of annual energy demand. With respect to the external walls, the optimized U-values completely change with the distribution of the climate zones. The recommended optimal values for various climate zones of China are also specified as design references for this type of underground buildings in terms of the building energy efficiency.

1. Introduction

In the view of the significant increases of the population in urban cities over recent decades, underground buildings have played an increasingly important role in the development and improvement of metropolises. A growing number of underground buildings, such as underground parking spaces, shopping malls, hospitals, railways, and office buildings, have been constructed as alternatives for urban area expansion in metropolises worldwide (Nezhnikova, 2016), and especially in China (Zhao et al., 2016, Yu and Ye, 2012). For instance, the total area of underground space in Beijing has reached 72.68 million m^2 with a noted annual increase of over 7.3 million m^2 based on published figures in August 2014 (Zhao et al., 2016). The development of underground buildings effectively relieves land utilization in these mega cities, and definitely provides more living space for urbanites (Shan et al., 2017; He et al., 2012). Moreover, compared to buildings built above the ground, underground buildings may exhibit increased advantages in terms of building energy efficiency and indoor climate owing to their better capacities for heat storage, heat stability, and smaller temperature variations (Staniec and Nowak, 2011; Delmastro et al., 2016). Therefore, underground buildings require lower heating and cooling loads, save more energy for residents, and improve urban sustainability (Staniec and Nowak, 2011; Delmastro et al., 2016; Alkaff et al., 2016). Many studies have demonstrated that underground buildings possess immense potential in reducing energy demands that can save more than 23% of energy in comparison with similar above-ground buildings (Staniec and Nowak, 2011; Al-Mumin, 2001; Barker, 1986; Christian, 1984). Specifically, the energy analysis of earth-sheltered domestic buildings situated in Poland showed that approximately 47–80% reduction in the heating energy demand could be achieved by using various thickness of thermal insulation (Staniec and Nowak, 2011).

Recently, some researchers have attempted to study the energy performance of underground buildings using various research methods such as a two–dimensional transient finite element model (FEM) to investigate heat loss in a basement (Wang, 1979), a two–dimensional dynamic model of heat transfer through building envelopes using MATLAB (Liu et al., 2010), a combination of computer programs FlexPDE and EnergyPlus to simulate the heating and cooling energy demands in earth-sheltered buildings (Staniec and Nowak, 2011), a

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three–dimensional analysis of the thermal resistance of an external insulation system of a basement (Maref et al., 2001), a three-dimensional finite difference model (FDM) to verify the energy reduction potential of underground buildings (Choi and Krarti, 2000), and an experimental analysis of indoor temperature variations related to ground layers in underground wine cellars (Tinti et al., 2014). All these experimental and simulated research studies indicates that the energy performance of underground buildings is determined by a wide variety of influential factors such as design typology, building function, covering soil depth and type, HVAC systems, thermal insulation, air infiltration (Alkaff et al., 2016). In terms of design typology, the contact surface area of building with the earth plays a key role in heat transfer. Overall, adopted methodologies have been more sophisticated as compared to conventional methodologies used for aboveground buildings. Additionally, these factors interact and change with different outdoor climates and indoor conditions (Alkaff et al., 2016; Peng et al., 2014). Among these factors, the building envelope is a factor that can be easily designed and optimized in the early design stages for energy efficiency.

In terms of building envelope features for aboveground buildings, an improvement in the thermal performance of the envelope, such as an increase in the thermal insulation level, can effectively reduce heat loss and the annual energy demands for both heating and cooling (Nielsen, 2005; Lin et al., 2016). The efficiency requirements for building envelopes, such as the assembly’s maximum U-value (overall heat transfer coefficient), are determined for building energy efficiency based on the ASHRAE Standards 90.1–2010 (ASHRAE, 2010) in America, and GB50189–2015 in China (GB50189, 2015). However, the heat transfer through an underground building is completely different from that of a building that is above the ground because the soil’s thermal properties are treated as a thermal reservoir for modulating interior temperatures (Ma et al., 2009). Therefore, these standards correspond to buildings built above the ground and might be not suitable for underground buildings in which the thermal performance of the envelopes is designed for energy efficiency.

In this context, several researchers have focused on the investigation of the influence of the thermal performance of the envelopes on energy consumption with respect to heating and cooling loads for underground buildings (Christian, 1984; Liu et al., 2010; Yuan et al., 2006; Staniec and Nowak, 2009). Krarti and Choi demonstrated that additional insulation is required at the corners, as opposed to the middle section of the surface to minimize the heat loss for underground buildings, and that insulation material should be close to the soil surface (Liu et al., 2010). Yuan et al. evaluated the effect of building materials on the temperature and heat flux for envelopes in a basement, and indicated that the thermal conductivity of building materials is an important factor in the heat transfer of the envelopes (Yuan et al., 2006). Dronkelaar stated that the energy performance is more significantly dependent on the U-value of the constructions and the ventilation rates in certain colder climates (Christian, 1984). Staniec and Nowak suggested that thinner thermal insulation, elicits a better cooling effect gained from the soil, whereas a thicker insulation leads to a smaller heating energy demand (Staniec and Nowak, 2011, 2009). These studies indicates that the thermal performance of the envelopes in an underground building is one of the most important design criteria to allow the best thermal comfort effect (Alkaff et al., 2016). However, the relationships between the annual energy demand and the thermal performance of the envelopes in underground buildings might not be very accurate and explicit, especially with respect to various climatic zones. In general, outdoor climatic conditions have a slight influence on the indoor environment and energy demand for underground buildings in a short time. However, the long-term distribution of ground temperature is crucial in determining the energy demand, which is dependent on the climate and soil’s thermal properties. Although the simulated analysis by Staniec and Nowak illustrated the influence of thermal insulation on heating and cooling loads, the combined effect of thermal performance of the envelope on the annual energy demand (a sum of heating and cooling energy) has not been considered in their study. Furthermore, their simulation was only performed for Polish climate conditions, and thus, it may not be possible to apply their conclusions to various climates around the world.

On the other hand, China has a vast territory spanning five different climatic conditions (Cui et al., 2017). Specifically, temperature waves of underground spaces differ in terms of values, amplitude, period, and phase displacement for various climatic zones. Therefore, the efficiency requirements of building envelopes in an underground building may vary significantly with changes in the climates. Hence, a reasonable and formal guideline, or a standard listing the efficiency requirements, are necessary for underground building envelopes in various climates to provide a basis for the energy-saving design of the envelopes, which is currently lacking in China.

The aim of this study is to investigate the influence of the thermal performance of the envelopes on annual energy consumption for underground office buildings in various climatic zones of China, thereby allowing the determination of the optimized U-value for building envelopes (including the roof and the exterior wall), and introducing reasonable guidelines for the energy efficient design envelopes with respect to underground office buildings. First, a building energy simulation tool known as the Designer's Energy Simulation Tool (DeST) is presented in detail to simulate the thermal process within the underground building and the accuracy of DeST is also validated by measured data. Thereafter, DeST is used to calculating the hourly heating and cooling loads for ground-buried office buildings to optimize the thermal performance of the insulation configurations of envelopes for various climatic zones in China, based on the annual energy consumption.

2. Methodology

This section is organized in four parts. Section 2.1 describes the details for simulating heat transfer for an underground building by means of DeST. Section 2.2 presents a prototype underground building model implemented in the DeST platform. Section 2.3 shows the classification of climate zones in China and lists the ten major Chinese cities selected for this simulation. The evaluation method of calculating annual energy demand based on hourly heating and cooling loads is summarized in Section 2.4.

2.1. Simulation tool

DeST is an effective building energy simulation tool that was developed by Tsinghua University in 1989. To-this-date, numerous case analyses and theoretical validations are performed, and as a result, DeST has become a widely-used platform for calculating building thermal processes and for dynamic simulations of the building’s energy distribution. Specifically, DeST develops a graphical user interface that is based on AutoCAD for all simulation processes to avoid additional modelling work and information loss due to conversion (Yan et al., 2008).

In terms of energy performance of an underground building, the key is to calculate the heat transfer of ground-coupled envelopes that are all in contact with the earth. This is the most significant difference for simulating an underground building and an aboveground building. Generally, heat transfer within ground-coupled envelopes is typically computed using numerical methods, such as FEM and FDM (Wang, 1979; Choi and Krarti, 2000). However, these numerical models are excessively time-consuming for hourly simulations over the period of a year (Yan et al., 2008).

In DeST simulation, the frequency response analysis (FRA) method is adopted to compute the heat transfer of ground-coupled envelopes under unsteady boundary conditions quickly and correctly (Xie et al., 2008). The schematic diagram of an underground building is presented in Fig. 1 and the boundary conditions for heat transfer are also shown in this figure. At the upper condition, the outdoor ground surface