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Improving building facade design using integrated simulation of daylighting, thermal performance and natural ventilation

Wei You, Menghao Qin (✉), Wowo Ding

School of Architecture and Urban Planning, Nanjing University, Hankou Road 22, Nanjing 210093, China

Abstract

The opening of building facade has a strong influence on energy consumption. However, making full use of solar energy and natural wind to reduce energy consumption is a challenge for architects. The aim of this study is to investigate the influence of the facade design on energy consumption from an operable aspect. The evaluation comes from an integrated approach combining daylighting, thermal performance and natural ventilation. The study is based on computer simulation technique utilizing simulation tools EnergyPlus and Fluent. To facilitate the use of EnergyPlus, a simple graphic user interface has been developed by Matlab. The interface can set the parameters of EnergyPlus and process the wind pressure coefficients calculated by Fluent. With this interface, three type facade configurations with different areas or position changes have been modelled. The results show that opening area, compared with opening positions, exerts a greater influence on energy consumption. The opening position changes have a positive influence; however, this influence is small: at around 2%.

Keywords

building facade design,
daylighting,
thermal performance,
natural ventilation,
energy simulation

Article History

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1 Introduction

The opening design on building facades has a great influence on daylighting, solar heat gain and natural ventilation, which are closely related to the lighting and air conditioning energy consumption. However, in designing building facades, architects usually pay more attention to the aesthetic aspects, while neglecting the influence of opening forms on energy consumption. Since the oil crisis in 1970s, greater social focus has been placed on energy and environmental problems. Architects have also considered how to effectively use solar energy and natural wind to reduce energy consumption, thus the relationship between the opening forms of building facades and energy consumption requires intensive research.

Based on computer simulation technology, researchers have already analyzed the relationship between design factors (window size, glass material) and energy consumption (Zain-Ahmed et al. 2002; Li et al. 2005, Ravikumar and Prakash 2011), and some simple experiential models have been established to quickly predict the energy consumption (Catalina et al. 2008; Jaffal et al. 2009, Rijal et al.2011). However, in these studies, there is not enough attention paid to facade design from an operable aspect. Moreover, researchers often use abstract design control parameters, such as the ratio of the volume to the exterior wall area, window-to-wall ratio, or heat transfer coefficients, etc. In practical construction activities, however, those abstract parameters are of little use to detailed design. Meanwhile, simple facade opening forms (e.g., a simple middle rectangular window) cannot meet designers' requirements on variable building facade designs. Therefore, the principle that the change of the opening shape and position of building facade affects energy consumption needs to be analyzed more intensively, with possible facade design strategies explored. The facade opening in the building design domain contains abundant content, like the fixed window which can only get daylight, operable window which can get daylight and natural ventilation, ventilation cave which can only get natural ventilation. In this research, the facade opening is window opening, including the fixed and operable window.

To accurately quantify the influence of opening forms of building facades on the integrated lighting, heating and cooling energy consumption, computer simulation techniques

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E-mail: mqin@nju.edu.cn

have been adopted in this research. The simulation tools used are EnergyPlus (US Department of Energy 2012) and Fluent (2002), which simulate the annual energy consumption and natural ventilation pattern (Woloszyn and Rode 2008). EnergyPlus is a novel simulation program which can comprehensively analyze thermal, daylighting and natural ventilation. However, when EnergyPlus simulates the natural ventilation with multizone network module, the default wind pressure coefficient values are based on ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) database and analytical models, which are very limited in evaluating the influences of detailed facade designs and building form changes. Besides, EnergyPlus unfortunately has no convenient graphic user interface, and parameter settings are very complicated. Commonly used interfaces, such as Ecotect (Autodesk 2010), DesignBulider (DesignBuilder Software 2012) etc., are limited in the simulation capability and fail to control the module parameters of EnergyPlus effectively.

This study examined the method of using CFD (computational fluid dynamics) to provide detailed wind pressure coefficient values to EnergyPlus, with a simple user interface, programmed by Matlab. The interface sets all needed module parameters of EnergyPlus and processes the data of the wind pressure coefficient calculated by CFD. A simple dual-rectangular space can then be built as simulation rooms to analyze the effects of different opening form changes on the energy consumption under different conditions, such as daylighting and ventilation, non-ventilation and non-daylighting.

2 Simulation method

2.1 Daylighting and natural ventilation model

2.1.1 *Daylighting model*

For daylight calculation, a web-based survey (Reinhart and Fitz 2006) indicates that 79% participants who were considering daylighting used computer simulation technology, and over 50% of the programs used the Radiance (Ward and Shakespeare 1998) simulation engine. It reveals that Radiance is predominant in the daylight simulation community. Radiance is a powerful lighting simulation system for the analysis and visualization of lighting in design. It uses backwards ray-tracing technique to calculate scene illuminance and has the ability to simulate complex lighting environment of complicated geometry (Compagnon 1997). The accuracy of Radiance has been validated and it has proved that Radiance is suitable to predict internal illuminance for a range of sky conditions (Mardaljevic 2000). So many researchers use Radiance to calculate daylight factor and interior illuminance distribution at certain time (Dubois 2003; Samant and Yang 2007). Moreover, the Radiance program can also be coupled with thermal simulation software to calculate the global energy savings (Bodart and De Herde 2002). However, the coupling process is very complex and thus is not selected in this study.

In order to quantify and evaluate the daylighting schemes, some daylighting algorithms have been incorporated in building energy simulation programs, which could predict the illuminance, light power reductions, and the associated thermal load interactions, like EnergyPlus (2009). This module is able to simulate hourly-varying interior illuminance, window management for solar gain, and the operation of lighting control systems. In 2005, an experiment was carried by Loutzenhiser et al. (2007) to validate these daylighting calculations. The conclusion points out the daylighting algorithm can predict with some accuracy daylight illuminance and the associated interactions. And "Building energy simulation programs can also be very valuable tools in the design phase of a new building to assess potentially daylight control savings by performing parametric studies, varying windows and shading devices to optimize the energy performance of a building." So this daylighting model is selected in this research.

2.1.2 *Natural ventilation model*

For natural ventilation in buildings, a recent review reveals that CFD technique is one of the most popular simulation methods (Chen 2009). The CFD simulation can provide high grid resolution for airflow domains, which allows detailed analyses in geometry and can accurately calculate the pressure and velocity. These capabilities enable CFD method to be used to study indoor air quality, natural ventilation and stratified temperature, which are difficult to be predicted by other models. In addition, the boundary conditions (solar gain, heat transfer, inner wall temperature) have to be defined by field measurements or provided by other simulation tools. So CFD programs have been coupled with other energy simulation tools to predict the airflow rates for zones with a highly non-uniform pressure distribution (Wang and Chen 2005). For example, Pappas and Zhai (2008) coupled a building energy simulation program with a CFD package to analyze the thermal performance of double skin facade cavities with buoyancy-driven airflow. Wang and Wong (2009) externally coupled CFD with ESP-r (University of Strathclyde 2012), an integrated energy modelling tool for the simulation of the thermal, visual and acoustic performance of buildings, to better predict indoor thermal environment. However, the parameter exchanges between the two simulation programs are complex and the simulation is time consuming (Sreshthaputra et al. 2004).

Another type of airflow model for natural ventilation is the network model, like the most commonly used COMIS (Feustel 1999) and CONTAM (Walton and Dols 2005). These models can analyze building airflow, pressure difference, and contaminant transport rates by solving mass, energy and chemical-species conservation equations. Because of these capabilities, the models are often coupled with thermal models like TRNSYS (Klein et al. 2004). TRNSYS is a graphically based software environment used to simulate the behavior of transient systems, and TRNSYS is used in conjunction with COMIS by implementing COMIS as a subroutine (Sonal 2006). Moreover, CONTAM's predecessor, AIRNET (Walton 1989), forms the basis of the network model now included with EnergyPlus and ESP-r. The network model in EnergyPlus is called Airflow Network module and the network model in ESP-r is called "mfs" module. When performing multizone simulation, each zone is described as a "node" in the model, and the simulation could reach a very fast convergence speed. The accuracy of the models has also been validated by many experiment studies (Johnson 2010). The testing results show that the current airflow tools (COMIS, CONTAMB, ESP-r and EnergyPlus) can be used to model single zone and muti-zone wind-driven ventilation, single zone buoyancy-driven cross ventilation, combined-driven cross ventilation, etc. However, the simulation accuracy is heavily dependent on some ambiguous coefficients. Adjustment of these coefficients can improve the model's accuracy.

This study analyzes not only the opening size but also the opening position. A series of different design schemes will be simulated. CFD coupled energy simulation technology might be unsuitable for this research due to its time cost, and the network model is selected as the natural ventilation model, although it might be less accurate than CFD coupled technique. However, in the early design phase, the network model will be accurate enough to access to the potential energy savings.

2.2 Matlab-based simulation program

In this research, the simulation parameters in EnergyPlus consist of 12 items, with a total of 43 sub-items. The major setting contents of each module are listed in Fig. 1, and please refer to the EnergyPlus Input and Output Reference Manual for the detailed parameter settings (EnergyPlus 2009).

2.2.1 *Daylight simulation parameters*

The DELight module of EnergyPlus has been adopted in this study. The input parameters required in this model include: lighting control type (continuous, stepped, and continuous/off), maximum and minimum light powers, daylight reference points, and illuminance setpoint at reference points. The lighting control type is set to continuous dimming and the power of the illumination equipment ranges from 3 W/m^2 to 30 W/m^2. The reference point is set at the axis of a room, and there are two reference points in each room, one is 1 m away from the outer wall of the room

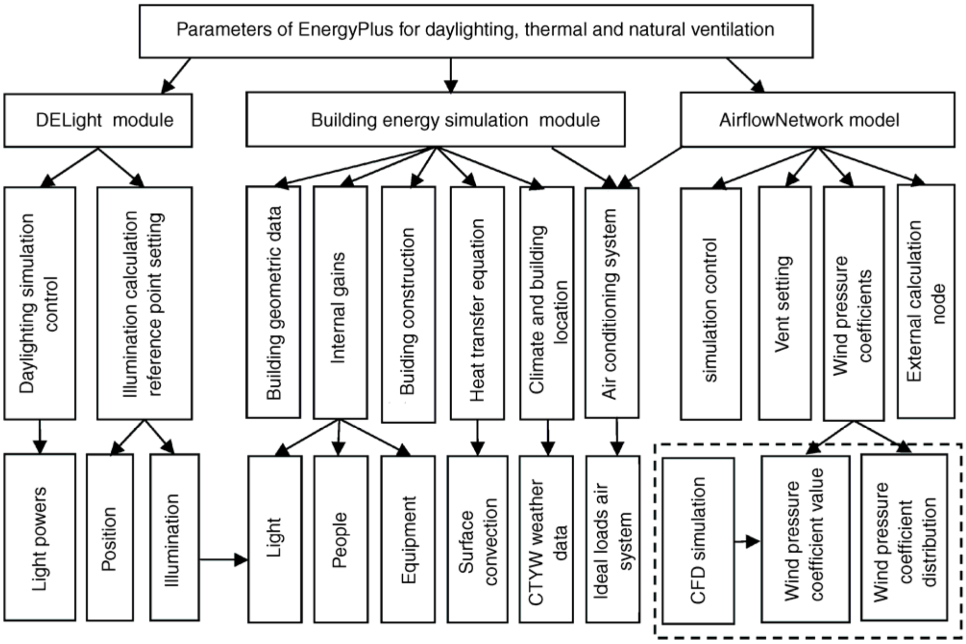


Fig. 1 Major parameters setting of daylighting, thermal and natural ventilation simulation modules of EnergyPlus

and the other is 1 m away from the inner wall of the room. They are all at 0.9 m height. The required illumination of the working plan is set to be 500 lx (Alzoubi and Al-Zoubi 2010).

2.2.2 *Multizone network model and C_p calculation*

The multizone network model in EnergyPlus is controlled by AirflowNetwork module objects. The simulation control in this research is multizone without distribution. In this control, AirflowNetwork module objects will simulate multizone airflows driven by wind during simulation timesteps. And the ventilation control mode is temperature dependent. All of the zone's openable windows and doors are opened if $T_{\text{zone}} > T_{\text{out}}$ and $T_{\text{zone}} > T_{\text{set}}$ (T_{out} equals the outdoor air temperature, T_{zone} equals the previous timestep's zone air temperature, T_{set} equals the vent temperature schedule value) and venting availability schedule allows venting. The venting availability schedule value is set to 1 all through the year, which means venting is allowed all the year. The vent temperature schedule value is set slightly above 18℃. So the window will be opened automatically by EnergyPlus according to the indoor and outdoor temperature. When the window or door is closed, crack flow is assumed. The following power law form is used that gives airflow through the crack as a function of the pressure difference across the crack (EnergyPlus 2009):

$$Q = C_Q(\Delta P)^n \tag{1}$$

where Q is the air mass flow rate (kg/s), C_Q is air mass flow coefficient (kg/(s·m), @ 1 Pa), ΔP is the pressure difference across crack (Pa), n is the air mass flow exponent (dimensionless). In this research, the air mass flow coefficient and air mass flow exponent are set 0.001 and 0.65 respectively by default.

For natural ventilation model, wind pressure is an important boundary condition, as wind is an important driving force for infiltration and ventilation. The wind pressure P_{w} acting on the building envelope openings is usually expressed by the pressure coefficient C_{p} (Cóstola et al. 2009), which can be defined as follows:

$$C_{\text{p}} = \frac{p_{\text{w}} - p_0}{0.5\rho U_h^2} \tag{2}$$

where P_0 is the static reference pressure (Pa), ρ is the air density (kg/m^3) of the approach wind and U_h is the reference wind velocity (m/s) taken at the height h of the building. Cóstola et al. (2009) classifies the source of the wind pressure coefficient into two types: first-hand data and second-hand data. The first-hand data are obtained by measurement and CFD simulation, while second-hand data, such as databases and analytical models, are usually based on the compilation of wind-tunnel tests. EnergyPlus provides default C_{p} values, which is called "Average-surface Calculation", based on ASHRAE database (ASHRAE 2001) for high rise buildings and analytical model developed by Swami and Chandra (1988) for low rise buildings. These coefficients can be used only for rectangular buildings and are not position dependant. So they are very limited for this study. In this study, the CFD simulation technology is used to provide the needed wind pressure coefficients and a program is written by Matlab to process the data between the CFD software "Fluent" and energy simulation software "EnergyPlus".

2.2.3 *Data processing code*

The simulation procedure consists of four main steps as shown in Fig. 2. Four main scripts are written by Matlab for automatic running of the simulation.

The first Fluent setup script will generate a Fluent case file which defines the building geometry, boundary conditions and the simulation control parameters and a batch file which starts up the Fluent software. In this study, 12 pressure coefficient values (30° intervals) will be set in EnergyPlus. Because of the symmetry of the model, only four approaching wind directions (0°, 30°, 60° and 90°) have been simulated instead of all 12 wind directions. The computational domain, boundary conditions, etc. used in these simulations will be discussed in the next section.

After CFD simulation, wind pressure values will be extracted and processed from the simulation result by the wind pressure coefficients (WPC) processing script1. To extract the wind pressure distribution data, the script first generates a calculation grid file capable of being identified by the CFD software. After input of the grid file, the CFD software calculates the wind pressure value. Next, the script extracts the wind pressure distribution values and performs matrix processing to obtain wind pressure distribution graphs corresponding to the building facades.

To calculate the wind pressure coefficients of window openings, the WPC processing script2 extracts the size and position of the window hole according to the input

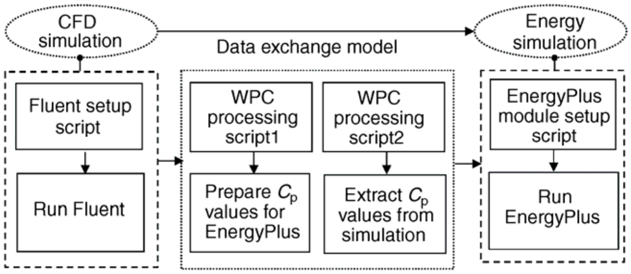


Fig. 2 Simulation procedures coupled with EnergyPlus and Fluent

parameters and calculates the corresponding wind pressure coefficient values according to Eq. (2). To facilitate the operationalization, the program is designed to automatically output the WPC values for 12 wind directions according to the parameter setting formats of EnergyPlus. As the position of the window opening changes, the wind pressure coefficient values are modified correspondingly.

The other EnergyPlus models (thermal, daylighting and ventilation) and building geometry parameters will be defined by the EnergyPlus module setup script. Then the "idf" file of EnergyPlus will be generated by the script.

2.3 Simulation-based C_p value accuracy analysis

CFD simulation is a good method to provide wind pressure coefficient, and some previous researches have studied the simulated accuracy of C_p values by compare the experiment and simulation results (Lim et al. 2009; Köse and Dick 2010). However, many researchers select to use large eddy simulation (LES) technology to get better simulation results, and the grid number is very high in the CFD model construction. So the inlet conditions are very sophisticated and the simulation is very time consuming. It may have problem in the design phase, because in the design process, many design cases need to be compared and the time is very limited. So some simplified CFD model is adopted. In order to evaluate the CFD approach that we used, we compared our simulation results with the surface distribution data measured by Richards and Hoxey (2012). The surface distribution data are the on-site full-scale measurements at a 6 m cube. And the measured points are on the vertical and horizontal centreline section for wind direction sectors of 15°.

2.3.1 *CFD model*

In order to compare with the Richards and Hoxey's surface distribution data, we also use a 6 m cube as simulation object for the CFD model. The computational domain size and the boundary condition are all set according to the AIJ (Architectural Institute of Japan) guideline (Tominaga et al. 2008), as shown in Fig. 3. According to AIJ guideline the inlet vertical velocity profile on flat terrain is usually given by a power law, but for a 6 m cube simulation, the wind is modeled as a uniform profile with a speed of 2.0 m/s (Seifert et al. 2006). The elements number of meshes is 80320. To identify the appropriate turbulence model and grid mesh type, two different turbulence models (RNG, standard k-ε) with two mesh types (hexa unstructured, hexa cartesian) are used in this evaluation exercise. For the convergence criteria, 0.001 is set as a tolerance value and the maximum number of iterations is set to 10 000.

2.3.2 *Comparison of C_p values*

Figure 4 shows the comparison of C_p value distribution between computational and experimental results with the

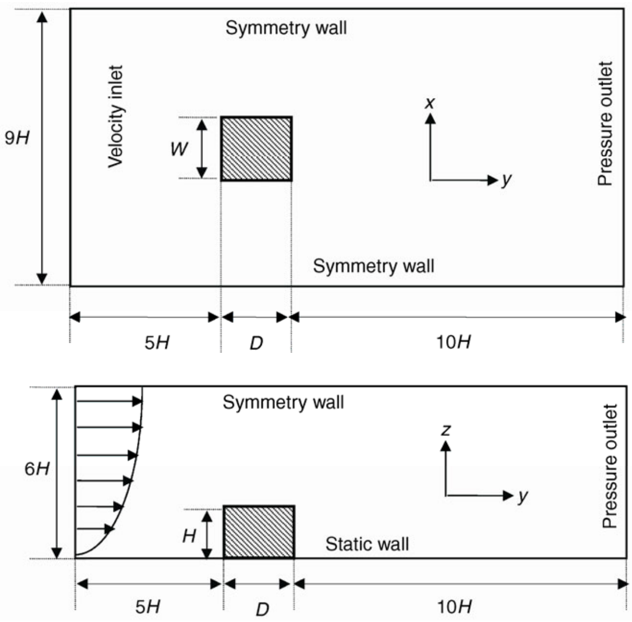


Fig. 3 Schematic representation of the computational domain and boundary conditions

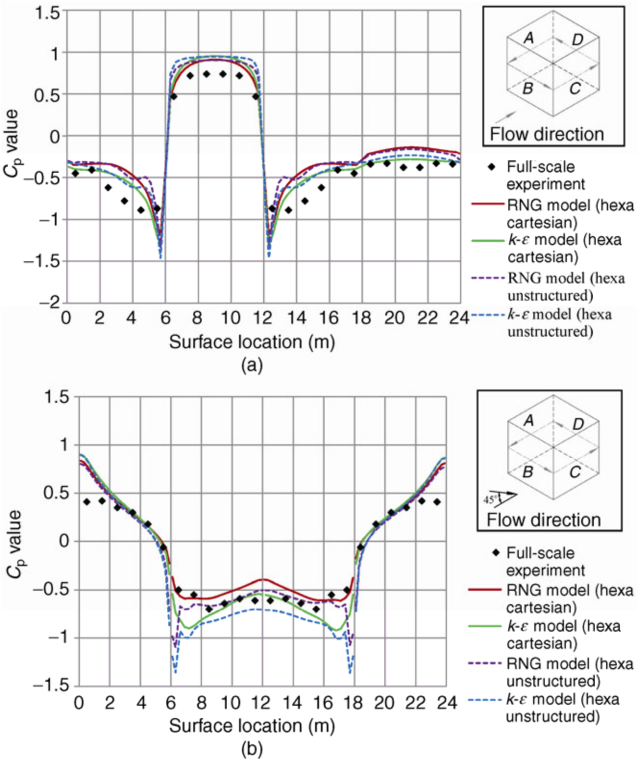


Fig. 4 Comparison of wind pressure coefficient on the cube (6 m) surface between computational and experimental results (Richards and Hoxey 2012) with the wind direction of (a) 0° (along the line *A*–*B*–*C*–*D*) and (b) 45° (along the line *B*–*C*–*D*–*A*)

wind direction of 0° and 45°. The agreement between the two results is reasonably good. However, due to the differential equation for the eddy viscosity and the improved ε-equation, the RNG model shows much better results than the standard k-ε model. And the hexa cartesian grid mesh type shows some better results than the hexa unstructured grid mesh type. This may be due to the differences between the skewed elements meshed by the hexa unstructured type and the equilateral elements meshed by the hexa cartesian type. And the simulated C_p values are relatively higher than the measured results. So in this research, the hexa cartesian grid mesh type is selected in the following case study.

3 Primary analysis of the opening form of building facades

3.1 Model geometry

3.1.1 Simulation room

Because the aim of this study is to primarily obtain the overall principle of how the opening form of the building facade influences the building energy consumption, the simulation results will provide a basis for further research. To simplify the simulation, a dual-rectangular space is selected as building model for the analysis, wherein the building is aligned south-north direction. The model is able to reflect the daylight and solar heat gain features of south and north direction rooms and airflow features of multizones. The two rooms are all set to be 3.6 m in width, 4.5 m in length and 3.6 m in height. The room size is very common used in the design domain. For example, the room can be used as the house's bedroom, and can also be used as a standard office room, moreover, the size accord with the design modulus.

3.1.2 Sizes and positions of openings of building facades

The changes of building facade openings include two aspects: window area and window position. The determination of the window area is simple according to the criteria, building structure, use habits, etc., but the latter is variable, which is more difficult to control. If the change scale is too large, the influence principle of the facade design on energy consumption may not be obtained. If the change scale is too small, however, unnecessary work labour will be increased. Thus, a primary analysis is made in this research, and the analysis results can be used as a basis for further possibility analysis of the opening forms of building facades.

In this study, three window opening configurations with different areas or positions are simulated, as shown in Fig. 5. The facade design needs to consider the constructive factors. For example, the structural beam needs to be reserved. The initial windows have the same window-to-wall area ratio and operable-to-fixed window area ratio. The changing window openings are on the south wall. Facade A1 is used as the Case A and Case B's north wall. Facade C6 is used as the Case C's north wall.

3.2 Building construction

The construction of the protective structure is set according to the domestic building construction way in common use at present, as shown in Table 1. The data are all get from an energy saving calculation report of a real residence project. The inside and outside surface convective heat transfer coefficients are calculated by the inside and outside SurfaceConvectionAlgorithm in EnergyPlus. The simulation models in this research are all set by default. And the solar factor for direct transmission is 0.53.

3.3 Internal gains

Indoor heat gains are mainly composed of people, lighting and equipment. To facilitate calculation and comparison, the domestic "Design Standard of Energy Efficient Designing for Public Buildings" has detailed specifications on the three heat gains of different building types (GB50189 2005). In this research, the common office is taken as an example for simulation. And the internal heat gains of lighting, people and equipment are set 11 W/m^2, 4 W/m^2 and 20 W/m^2 respectively.

3.4 HVAC system

Heating, ventilating and air conditioning (HVAC) system is complicated in EnergyPlus. However, they are not important in this research, so the relatively simple Ideal Loads Air System is adopted, controlling the heating temperature of the room to be 18℃ and the air conditioning temperature to be 26℃. The outdoor air object is set to NoOutdoorAir by default, and the outdoor airflow rate object is set to autosize.

3.5 Climate data

Simulations were performed with climatic data of three cities: Beijing, Nanjing and Guangzhou. They are the typical cities of three climate zones in China. Beijing is in the cold zone, Nanjing is in the hot summer cold winter zone and Guangzhou is in the hot summer warm winter zone. In this study, the Chinese Typical Year Weather (CTYW) data are used to simulate annual building heating and cooling energy. The data are based on the data from 1982 to 1997 obtained from the US National Climatic Data Centre (Zhang and Huang 2004).

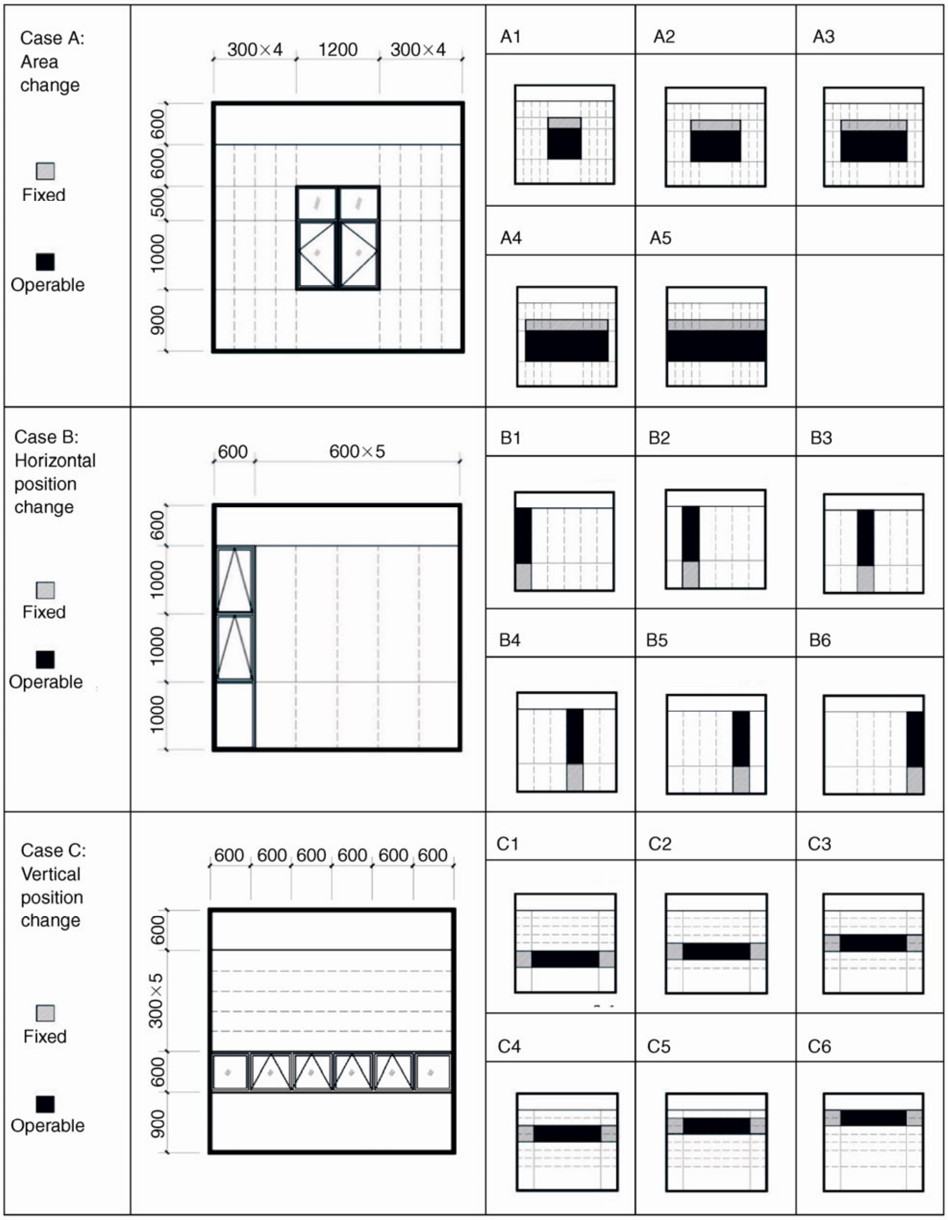


Fig. 5 Proposed window opening configurations (unit: mm)

Table 1 Thermophysical properties of the construction elements

Protective structure	Major material	α	λ (W/(m·K))	ρ (kg/m³)	c (J/(kg·K))
Roof	Foaming ceramic insulation board (120 mm)	0.5	0.08	280	1000
	Waterproof coiled material (3 mm)	0.92	0.170	600	2842
	Reinforced concrete (120 mm)	0.65	1.74	2500	2500
External wall	Painting (2 mm)	0.25	0.93	1700	1911.5
	Self-insulation building blocks (220 mm)	0.65	0.268	1200	560
	XR organic insulation mortar (10 mm)	0.65	0.052	184	1170
Ground	Cement plaster (20 mm)	0.68	0.93	1800	1050
	Waterproof coiled material (10 mm)	0.92	0.170	600	2842
	Foaming ceramic insulation board (35 mm)	0.5	0.08	280	1000
	Reinforced concrete (100 mm)	0.65	1.74	2500	920

Note: The window body is a dual-layer hollow glass window (6 mm common glass+12 mm air+6 mm common glass). α: solar absorptance, λ: heat transfer coefficient, ρ: density, c: specific heat capacity.

4 User interface

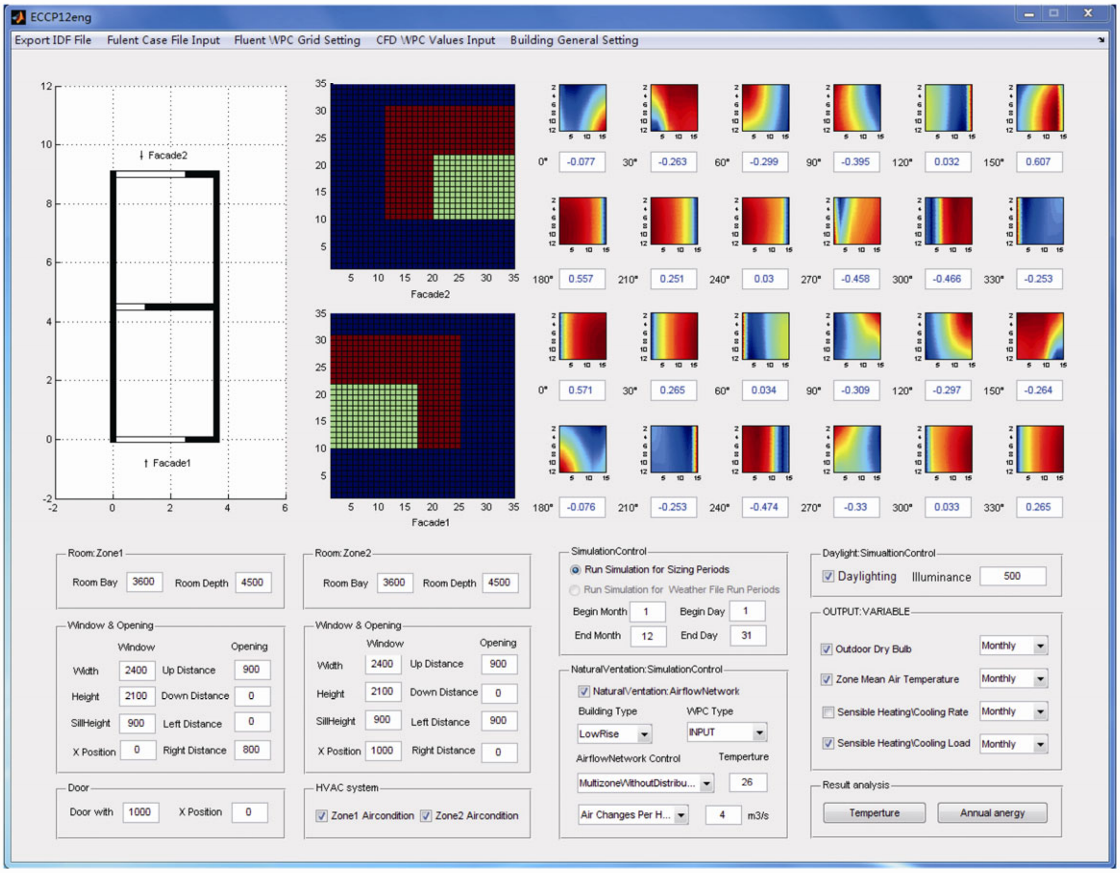
EnergyPlus as research software is complicated in parameter settings and lacks of user-friendly operation interface. To facilitate control over the parameters of EnergyPlus, we have developed a user-friendly graphic interface (GUI) by Matlab, as shown in Fig. 6. The input values on the main operation panel are parameters which need frequent modification when simulation is carried out, such as the size of the room and window body, the simulated time period, etc. The parameters which are rarely used or unfamiliar to architects, such as surface convection algorithm, zone HVAC systems etc. are hidden in the secondary operation panel.

To adapt to architects' visual thinking habits, the interface is provided with graphic windows to display the plane and facades of the building. In the facade display column, blue represents solid walls, red means glass, and green represents the part of window body that can be opened. Four rows of graphic windows at the up right of the interface display the wind pressure coefficient distribution diagrams of the windward side and the leeside in the 12 directions (30° intervals). With this simulation tool, the user can easily make intensive analyses of influences of facade opening forms on energy conservation via simple operation.

5 Simulation result analysis

5.1 Area change

The change of window area has a strong influence on the daylighting, solar heating gain and natural ventilation. As the opening area in the south wall increases, both the cooling and heating loads of the building change dramatically, as shown in Fig. 7–Fig. 9. Taking January and August in Nanjing as examples, from Case A1 to Case A5, the sensible heating energy reduces by 28.8% under the default C_p setting and by 29.2% under the CFD simulated C_p setting, while the sensible cooling energy increases by 39.4% (default C_p setting) and by 38.5% (CFD simulated C_p setting). It can be seen that as the south window area increases the solar energy can greatly reduce the heating load in the winter, but the solar radiation can also lead to more cooling load in the summer. Besides, the sensible heating and cooling energy loads change greatly at different locations. The most heating load is in Beijing and the most cooling load is in Guangzhou. Nanjing is in the middle, which the heating load is more than Guangzhou and the cooling load is more than Beijing. So we should adopt different design strategies for buildings at different climate zones. In Beijing, more



0°	-0.077	30°	-0.263	60°	-0.299	90°	-0.395	120°	0.032	150°	0.607
180°	0.557	210°	0.251	240°	0.03	270°	-0.458	300°	-0.466	330°	-0.253
0°	0.571	30°	0.265	60°	0.034	90°	-0.309	120°	-0.297	150°	-0.264
180°	-0.076	210°	-0.253	240°	-0.474	270°	-0.33	300°	0.033	330°	0.265

Room:Zone1: Room Bay 3600, Room Depth 4500

Window & Opening (Zone1):

	Window		Opening
Width	2400	Up Distance	900
Height	2100	Down Distance	0
SillHeight	900	Left Distance	0
X Position	0	Right Distance	800

Door: Door with 1000, X Position 0

Room:Zone2: Room Bay 3600, Room Depth 4500

Window & Opening (Zone2):

	Window		Opening
Width	2400	Up Distance	900
Height	2100	Down Distance	0
SillHeight	900	Left Distance	900
X Position	1000	Right Distance	0

HVAC system: ☑ Zone1 Aircondition ☑ Zone2 Aircondition

SimulationControl:
● Run Simulation for Sizing Periods
○ Run Simulation for Weather File Run Periods
Begin Month 1, Begin Day 1
End Month 12, End Day 31

NaturalVentation:SimulationControl:
☑ NaturalVentation:AirflowNetwork
Building Type: LowRise
WPC Type: INPUT
AirflowNetwork Control: MultizoneWithoutDistribu...
Temperture: 26
Air Changes Per H...: 4 m3/s

Daylight:SimuationControl: ☑ Daylighting, Illuminance 500

OUTPUT:VARIABLE:
☑ Outdoor Dry Bulb: Monthly
☑ Zone Mean Air Temperature: Monthly
☐ Sensible Heating\Cooling Rate: Monthly
☑ Sensible Heating\Cooling Load: Monthly

Fig. 6 EnergyPlus control interface

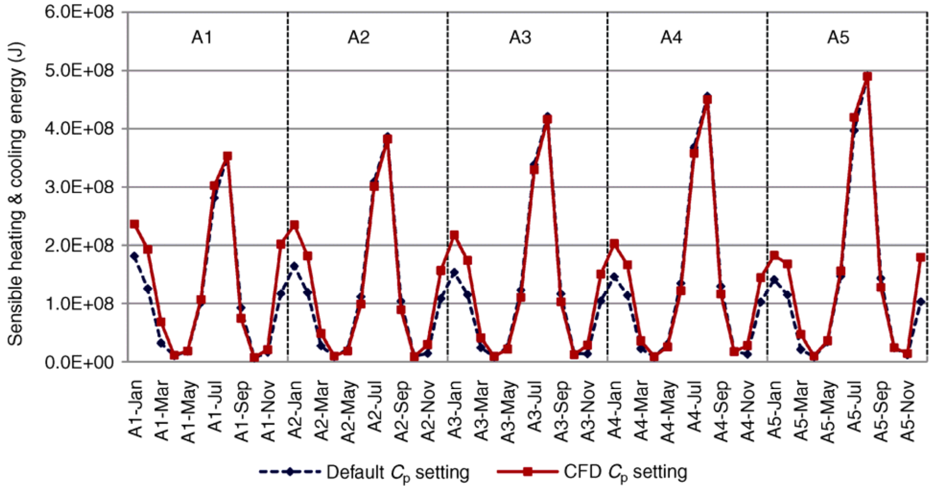


Fig. 7 Influence of area change on monthly sensible heating and cooling energy under the default C_p setting and CFD simulated C_p setting (Nanjing)

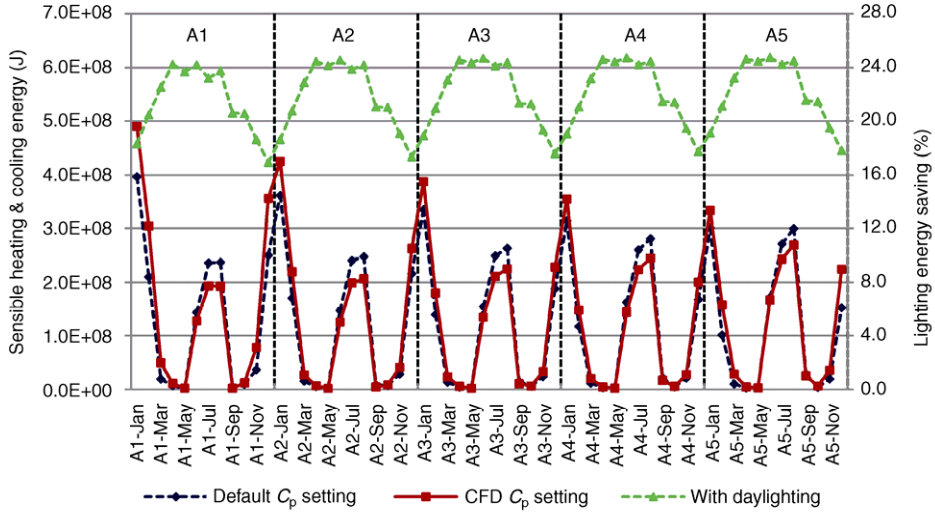


Fig. 8 Influence of area change on monthly sensible heating and cooling energy (simulated under the default C_p setting and CFD simulated C_p setting) and lighting energy saving by daylighting (Beijing)

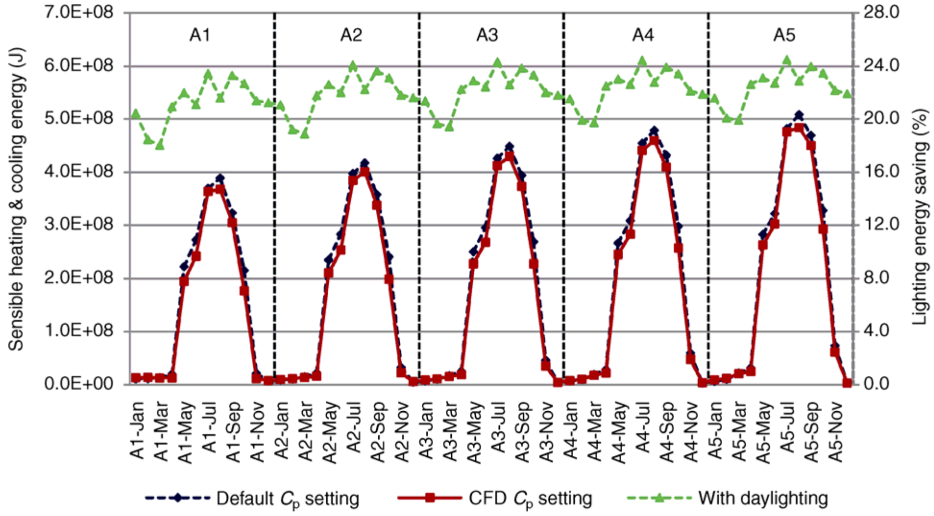


Fig. 9 Influence of area change on monthly sensible heating and cooling energy (simulated under the default C_p setting and CFD simulated C_p setting) and lighting energy saving by daylighting (Guangzhou)

attention could be paid to passive solar designs. And in Guangzhou, more attention could be paid to shading and natural ventilation designs. In Nanjing, design strategies for summer and winter should be considered at the same time. For the two C_p settings, the agreement between the two results is generally good on energy prediction. However, the sensible heating energy calculated under CFD simulated C_p setting is relatively higher than the energy calculated under default C_p setting. This may be caused by the higher C_p value calculated by CFD method, which leads to more infiltration when the window is closed. Because the ventilation control mode is temperature dependent, and in the winter, the window is closed in most time, and in the summer, the window is opened in most time.

As the opening area in the south wall increases, both cooling and lighting energy savings change significantly when there is natural ventilation and daylighting, compared with no natural ventilation and no daylighting. Take Nanjing as an example, as shown in Fig. 10. The cooling energy saving by natural ventilation varies greatly in different months. In April, the cooling energy saving could reach 73.3%, but in August the cooling energy saving is only 9.8%. It is because the outdoor temperature in hot summer is very high and the cooling energy can't be saved by natural ventilation. As the opening area increases, the change of the cooling energy saving also varies greatly in different months. Taking April and August as an example, from Case A1 to Case A5, the sensible cooling energy saving by natural ventilation increases from 28.4% to 79.5% under default C_p setting in April; however, in August the sensible cooling energy saving increases only from 7.1% to 10.5% under default C_p setting. Because the reference points are set at the axis of the room, and the window is also in the middle of the wall, the Case A1 window can provide enough daylight for the reference points. And as the window area increases, the lighting energy saving does not change greatly. By simulation the lighting energy saving by daylighting increases only from 20.3% to 21.4%. But the total energy saving of interior lighting by daylighting is much high. What's more, outdoor daylight condition can also influence the change extent. The influence of area change is more obvious in Guangzhou than that in the other cities. Thus it can be concluded that the facade openings can effectively reduce the demands on cooling loads by natural ventilation in summer and the demands on lighting energy by daylighting in full year.

5.2 Horizontal change

The horizontal position change of building facade openings exerts slightly influence on air conditioning and lighting energy consumption in three locations. Figure 11 shows the monthly change of sensible heating and cooling energy under default C_p setting and CFD simulated C_p setting in Nanjing. It can be seen that the cooling energy changes little and the heating load increases when the window is located in the middle of the wall. Taking January in Nanjing as an example, from Case B1 to Case B4, the sensible heating energy increases by 7.2% under CFD simulated C_p setting. Although the change extent calculated under default C_p setting is less than the extent calculated under CFD simulated C_p setting, the change trend is in line with the results calculated under CFD simulated C_p setting. It is possible that different $\mathrm{C_p}$ values are used. The default values are based on wall center, while CFD simulated values are based on physical locations. As the outdoor wind direction changes at different time, the surface wind pressure profile changes. For a whole year, the

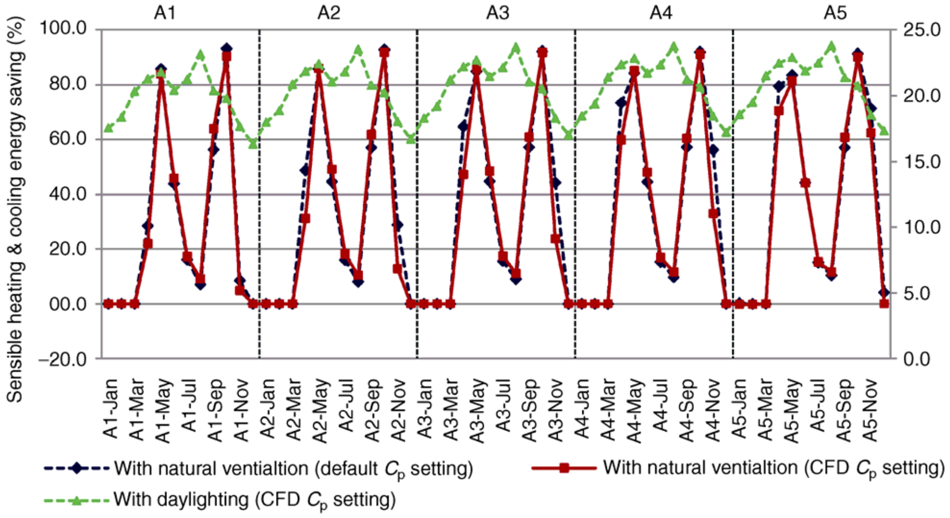


Fig. 10 Influence of area change on monthly energy saving by natural ventilation (simulated under the default C_p setting and under CFD simulated C_p setting) and lighting energy saving by daylighting (Nanjing)

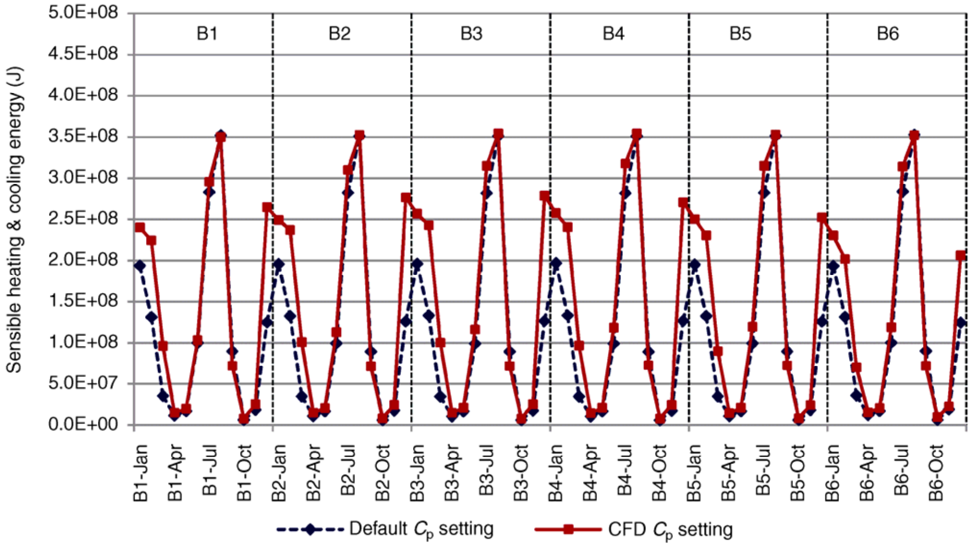


Fig. 11 Influence of horizontal position on monthly sensible heating and cooling energy simulated under the default C_p setting and CFD simulated C_p setting (Nanjing)

wind pressure is higher in the middle of the wall. When the window is in the middle of the wall, more infiltration takes place under the pressure difference. Compare with Nanjing, the heating load change in Beijing is more obvious. From Case B1 to Case B4, the sensible heating energy increases by 16.9% under CFD simulated C_p setting.

As the opening position moves horizontally, both cooling and lighting energy savings are greater when the window is located in the middle of the wall. The possible reason of cooling energy change may be as the same as the reason of heating energy change in winter. However the change extent is only about 2% for cooling and lighting energy saving under the CFD simulated C_p setting. Figure 12 shows the influence of horizontal position change on energy saving by natural ventilation and daylighting in Nanjing. For the lighting energy saving, different cities varieties greatly. In Beijing, the lighting energy saving is more than that of in other two cities, and the saving percent can reach more than 24% in summer months. From Case B1 to Case B6, the change extent can reach 3%. What's more, it is worth additional attention that the energy saving by natural ventilation varies greatly in different months due to different outdoor temperatures, wind speeds and directions. And in some transitional seasons (April, May, September, October)

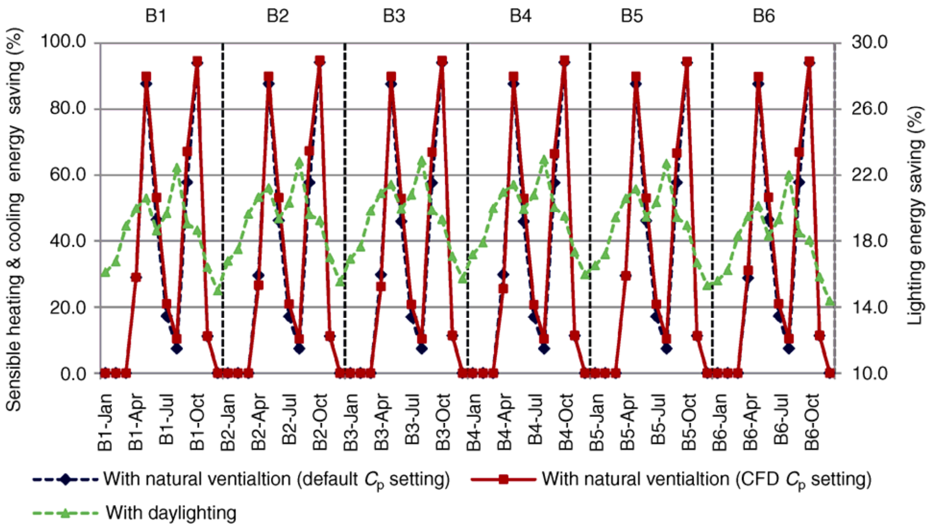


Fig. 12 Influence of horizontal position on monthly energy saving by natural ventilation (simulated under the default C_p setting and under CFD simulated C_p setting) and lighting energy saving by daylighting (Nanjing)

the cooling energy can vary by more than 8%.

5.3 Vertical change

Figure 13 shows the influence of the vertical position of facade opening on the monthly change of sensible heating and cooling energy under the default C_p setting and CFD simulated C_p setting in Nanjing. The vertical position change impact on energy consumption in the other cities is similar to that in Nanjing. Under the combined action of the heat and wind pressure, the influence of the vertical position change of facade openings on the heating energy consumption decreases significantly in comparison with that of the horizontal position change. Taking January in Nanjing as an example, from Case C1 to Case C6 the sensible heating energy reduces by 12.2% under the default C_p setting and by 21.8% under the CFD simulated C_p setting.

As to the energy savings by natural ventilation and daylighting, the cooling and lighting energy reduce a little when the opening position rises. The energy is saved about 1.5% for both cooling and lighting under the CFD simulated C_p setting. Figure 14 shows the influence of vertical position change on energy saving by natural ventilation and daylighting in Nanjing. For the lighting energy saving, as the window location is above the working plan, and the window area is large enough to provide enough daylight for the reference point near the outer wall of the room, the lighting energy saving does not change greatly as the window vertically rises.

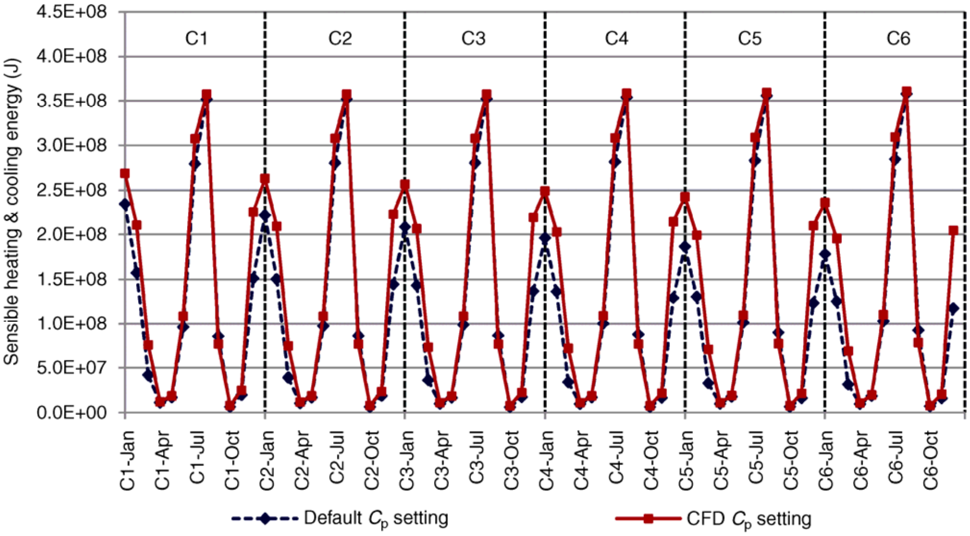


Fig. 13 Influence of vertical position on monthly sensible heating and cooling energy simulated under the default C_p setting and CFD simulated C_p setting (Nanjing)

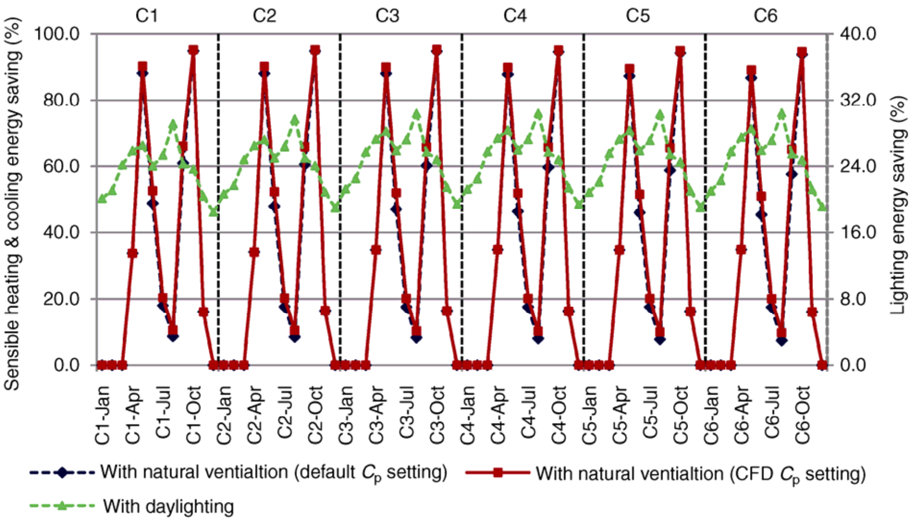


Fig. 14 Influence of vertical position on monthly energy saving by natural ventilation (under the default C_p setting and under CFD simulated C_p setting) and lighting energy saving by daylighting (Nanjing)

However, the influence of vertical position on lighting energy saving varies a little in different cities. In Guangzhou, the change percent can reach more than 2%. And In Beijing, the change percent can reach less than 1%. The cooling energy can also be saved more than 5% in some transitional seasons. The simulation results prove that: when the window positions rises, the energy consumption reduces gradually, but when the lower edge of the window rises to 1.5 m position, the energy consumption reduces quickly.

6 Conclusions

EnergyPlus is a very useful energy simulation software, which can synthetically analyze daylighting, thermal performance and natural ventilation. However, for natural ventilation, the C_p values used in the multizone network model are based on ASHRAE database and analytical models. The data are very limited in evaluating the influence of detailed facade design changes and building form changes. Using CFD to provide the detailed C_p values to EnergyPlus is explored in this paper. By comparing with default C_p setting, it is proved that this method is very useful to evaluate the design schemes by analyzing the effect of opening area and position changes on energy consumption. We should be careful when we use this method to calculate building heating energy, as the CFD simulated C_p values may cause more infiltration which will lead to higher heating energy. Furthermore, because the default C_p values are averaged over a whole surface, while the CFD simulated C_p values are averaged over window areas only, CFD simulated C_p values should provide more accurate prediction, which could reflect the opening position's influence nicely.

The study of opening forms of building facades proves that: the area of opening has the most influence on a building's energy consumption. As the opening area increases, the cooling load rises dramatically. So the window size is a major factor in the energy saving control. The solar radiation can directly get into the room through the window, which could greatly influence the heating and cooling load. Although the large south window can get more solar energy in the winter and more daylight, overheating may be got in the summer and the more energy could lose by heat conduction and infiltration. So for the building with large window size, natural ventilation and external shading should be considered sufficiently. In addition, the window construction and the glass material should be selected carefully in the design stage. The change of opening positions influences the daylighting and air conditioning energy consumption to some extent; however, in comparison with the influence of area change, the effect is small. When it comes to horizontal change of opening positions, the air conditioning energy consumption fluctuates at about 2%. When it comes to vertical change of opening positions, both air conditioning and lighting energy consumption reduce if the opening position rises.

Architects play an essential role in designing energy-efficient buildings. Good design will minimize a building's requirement for HVAC system and eventually save energy. The authors are carrying out a series of research to develop principles, tools, values and recommendations for architects, and help them to improve their design towards sustainability and health. This study is a primary analysis of the influence of facade opening forms on the building energy consumption. More research findings will be reported in the following papers.

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References

Alzoubi HH, Al-Zoubi AH (2010). Assessment of building facade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades. *Energy Conversion and Management*, 51: 1592 – 1599.

ASHRAE (2001). ASHRAE Handbook: Fundamentals. Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Autodesk (2010). Autodesk Ecotect Analysis. Available: http://usa.autodesk.com/ecotect-analysis.

Bodart M, De Herde A (2002). Global energy savings in offices buildings by the use of daylighting. *Energy and Buildings*, 34: 421 – 429.

Catalina T, Virgone J, Blanco E (2008). Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy and Buildings*, 40: 1825 – 1832.

Chen Q (2009). Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment*, 44: 848 – 858.

Compagnon R (1997). RADIANCE: A Simulation Tool for Daylighting Systems. The Martin Centre for Architectural and Urban Studies, University of Cambridge, UK. Available: http://radsite.lbl.gov/radiance/refer/rc97tut.pdf.

Cóstola D, Blocken B, Hensen JLM (2009). Overview of pressure coefficient data in building energy simulation and airflow network programs. *Building and Environment*, 44: 2027 – 2036.

DesignBuilder Software (2012). DesignBuilder. Available: http://www.designbuilder.co.uk.

Dubois MC (2003). Shading devices and daylight quality: An evaluation based on simple performance indicators. *Lighting Research and Technology*, 35: 61 – 76.

EnergyPlus (2009). EnergyPlus Manual: Documentation Version 3.1. US Department of Energy, USA.

Feustel HE (1999). COMIS—An international multizone air-flow and contaminant transport model. *Energy and Buildings*, 30: 3 – 18.

Fluent (2002). Airpak 2.1 User's Guide.

GB50189 (2005). Design Standard of Energy Efficient Designing for Public Buildings. Bejing: China Architecture and Building Press. (in Chinese)

Jaffal I, Inard C, Ghiaus C (2009). Fast method to predict building heating demand based on the design of experiments. *Energy and Buildings*, 41: 669 – 677.

Johnson M-HD (2010). Assess and Implement Natural and Hybrid Ventilation Models in Whole-Building Energy Simulations. MS Thesis, University of Colorado at Boulder, USA.

Klein SA, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, Mitchell JC, Braun JE, Evans BL, Kummer JP, et al. (2004). TRNSYS 16—A Transient System Simulation program: User Manual. Solar Energy Laboratory. University of Wisconsinet at Madison, USA.

Köse DA, Dick E (2010). Prediction of the pressure distribution on a cubical building with implicit LES. *Journal of Wind Engineering and Industrial Aerodynamics*, 98: 628 – 649.

Li DHW, Lam JC, Wong SL (2005). Daylighting and its effects on peak-load determination. *Energy*, 30: 1817 – 1831.

Lim HC, Thomas TG, Castro IP (2009). Flow around a cube in a turbulent boundary layer: LES and experiment. *Journal of Wind Engineering and Industrial Aerodynamics*, 97: 96 – 109.

Loutzenhiser PG, Maxwell GM, Manz H (2007). An empirical validation of the daylighting algorithms and associated interactions in building energy simulation programs using various shading devices and windows. *Energy*, 32: 1855 – 1870.

Mardaljevic J (2000). Daylight Simulation: Validation, Sky Models and Daylight Coefficients. PhD thesis, De Montfort University, UK.

Pappas A, Zhai Z (2008). Numerical investigation on thermal performance and correlations of double skin facade with buoyancy-driven airflow. *Energy and Buildings*, 40: 466 – 475.

Ravikumar P, Prakash D (2011). Analysis of thermal comfort in a residential room with insect proof screen: A case study by numerical simulation methods. *Building Simulation*, 4: 217 – 225.

Reinhart C, Fitz A (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings*, 38: 824 – 835.

Richards PJ, Hoxey RP (2012). Pressures on a cubic building—Part 1: Full-scale results. *Journal of Wind Engineering and Industrial Aerodynamics*, 102: 72 – 86.

Rijal HB, Tuohy P, Humphreys MA, FNicol JF, Samuel A (2011). An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints. *Building Simulation*, 4: 117 – 134.

Samant S, Yang F (2007). Daylighting in atria: The effect of atrium geometry and reflectance distribution. *Lighting Research and Technology*, 39: 147 – 157.

Seifert J, Li Y, Axley J, Rosler M (2006). Calculation of wind-driven cross ventilation in buildings with large openings. *Journal of Wind Engineering and Industrial Aerodynamics*, 94: 925 – 947.

Sonal R (2006). Performance evaluation of natural ventilation strategy in a north American climate. ASME International Solar Energy Conference (ISEC2006), Denver, USA.

Sreshthaputra A, Haberl J, Andrews MJ (2004). Improving building design and operation of a Thai Buddhist temple. *Energy and Buildings*, 36: 481 – 494.

Swami MV, Chandra S (1988). Correlations for pressure distribution on buildings and calculation of natural-ventilation airflow. *ASHRAE Transactions*, 94(1): 243 – 266.

Tominaga Y, Mochidab A, Yoshiec R, Kataokad H, Nozue T, Yoshikawaf M, Shirasawa T (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 96: 1749 – 1761.

University of Strathclyde (2012). ESP-r Version 11.1. Available: http://www.esru.strath.ac.uk/Programs/ESP-r.htm.

US Department of Energy (2012). EnergyPlus. Available: http://apps1.eere.energy.gov/buildings/energyplus.

Walton GN (1989). AIRNET—A Computer Program for Building Airflow Network Modeling, NISTIR 89-4072. Gaithersburg, USA: National Institute of Standards and Technology.

Walton GN, Dols S (2005). CONTAM V2.4 User Guide and Program Documentation, NISTIR 7251. Gaithersburg, USA: National Institute of Standards and Technology.

Wang L, Chen Q (2005). On solution characteristics of coupling of multizone and CFD program in building air distribution simulation. Paper presented at 9th International IBPSA Conference, Montréal.

Wang L, Wong NH (2009). Coupled simulations for naturally ventilated rooms between building simulation (BS) and computational fluid dynamics (CFD) for better prediction of indoor thermal environment. *Building and Environment*, 44: 95 – 112.

Ward LG, Shakespeare R (1998). Rendering with Radiance: The Art and Science of Lighting Visualization. San Francisco: Morgan Kaufmann.

Woloszyn M, Rode C (2008). Tools for performance simulation of heat, air and moisture conditions of whole buildings. *Building Simulation*, 1: 5 – 24.

Zain-Ahmed A, Sopian K, Othman MYH, Sayigh AAM, Surendran PN (2002). Daylighting as a passive solar design strategy in tropical buildings: A case study of Malaysia. *Energy Conversion and Management*, 43: 1725 – 1736.

Zhang Q, Huang J (2004). Chinese Typical Year Weather Data for Architectural Use. Beijing: China Machine Press. (in Chinese)