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A thermal performance analysis model for the design optimisation of high-performance glazed facades

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Abstract

Façade Engineering is becoming increasingly complex due to the growing domain of possibilities. The design process of finding an optimal façade solution could therefore be aided by computational means. To this end, a validated thermal performance analysis model of a typical office is constructed using EnergyPlus v4.0.0, followed by a parametric study to determine the performance of alternative façade technologies and to identify the optimal façade solution in terms of energy consumption. The numerical analysis provides a useful ranking of existing façade technologies. Moreover, the thermal analysis model serves as a preliminary model for our future work in developing a multi-objective selection and design optimisation tool based on whole-life value design criteria.

Keywords: High-performance façade technologies, thermal analysis, energy consumption, parametric study.

1 Introduction

Costly and complex bespoke facades are often used to satisfy the conflicting performance requirements arising from energy efficiency, occupant comfort and aesthetic demands. The growing number of façade components, materials, technologies and systems, however, are making it increasingly difficult to devise an optimal façade solution from the large domain of possibilities. It is therefore desirable to provide some computational means of assisting with the façade design process, particularly at early design stage, when the domain of possibilities is very large and design decisions have the largest impact on performance, environmental sustainability, and economy. Glazed openings are primary components for façade design due to their multi-functionality, but they introduce several conflicts into the design process. These conflicts could be resolved by the use of static and/or actively controlled glazed facades, which are based on high-performance materials and novel technologies.

A number of outdoor test chamber experiments were conducted to test façade technology performance [1-4]. They generally provide better predictions of real-world façade performance than laboratory work. However, there is a lack of validated parametric analysis of different competing façade technologies. This study explores the energy efficiency of seven high-performance façade technologies. Firstly, a preliminary thermal analysis model is constructed and validated. The numerical model is subsequently modified to simulate a typical office room. Finally, the effects of glazing area and orientation are investigated by modelling them individually using the modified numerical model, and a useful ranking is obtained by comparing the net energy consumption.

2 Preliminary thermal analysis model and validation

2.1 Introduction

The thermal performance analysis was carried out using EnergyPlus v4.0.0. In order to gain sufficient confidence in the accuracy of the simulation results, a preliminary model of a test chamber was constructed and validated using existing experimental data. Our thermal performance analysis model was validated with the experimental results obtained from the Energy Monitoring Company (EMC) test room project [4] for three reasons. First of all, the weather data was collected on site, and the measured internal performance data was collected at a relatively high frequency of once an hour. Secondly, the experiment set-up, such as geometry, wall construction, window types, and the HVAC system, was relatively simple, and thereby making it easier to construct the model and identify errors. Thirdly, the experimental data and the test facility description were well documented.

2.2 Description of the experiment

This section is summarised from Lomas et al [5], which provides a comprehensive description of the experiment. The test site was located in a rural field in Cranfield in Bedfordshire, UK. The rooms are constructed in pairs to even the experimental uncertainty, with an interchangeable panel on the wall facing 9° west of south (Figure 1). The performance data was collected in Room 1, 3, and 5.

The rooms are timber-framed, lightweight construction with insulation. The internal geometry is illustrated in Figure 2. Each test room consists of a room space and a room space. The south walls were installed with interchangeable panels, i.e., single glazing, double glazing and opaque panel. The room space was constructed to be well sealed, and the roof space was ventilated.

The experiments were conducted for two periods: the free-floating period (May 21 – May 30, 1990), when there are no heating resources, and the heating period (Oct 17 – Oct 26, 1987), when the rooms were heated by the oil-filled electric panel radiator. Six climate parameters were measured which are external air temperature, relative humidity, global solar radiation, diffuse horizontal radiation, wind speed, and wind direction. Relative humidity was not measured during the heating period experiments. It is therefore obtained from the Bedfordshire Weather Station located 19km from the test site.

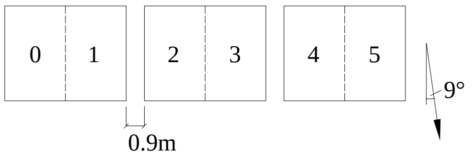


Figure 1: Plan view of EMC test rooms [5]

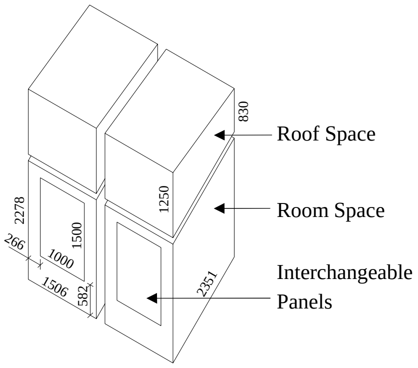


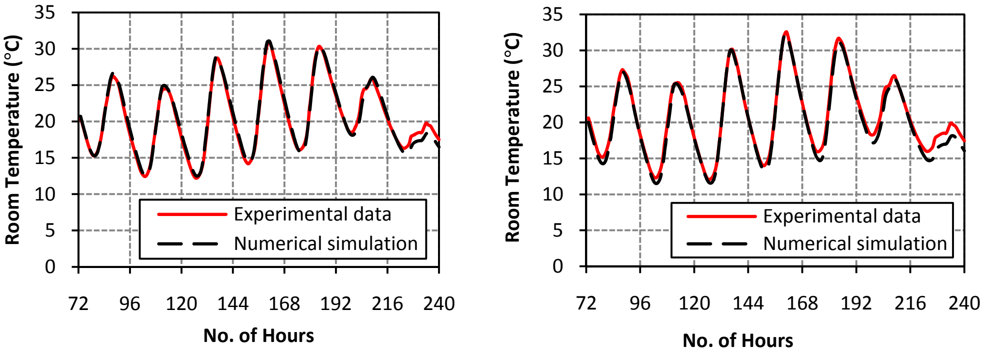
Figure 2: Test room internal geometry (mm) [5]

2.3 Description of the numerical model

The numerical model was constructed according to Section 2.2. The load convergence tolerance value was set to 0.04, and the temperature convergence tolerance value was set to 0.01. Time step is set to 3 minutes. Beam solar radiation is assumed to be distributed on each surface of the room. The interior convection model correlates the heat transfer coefficient to surface orientation and temperature difference between the surface and the room air. The exterior convection model calculates heat transfer coefficients from roughness, wind speed, and the site's terrain. The air change rate is assumed to be 0 and 1 ac/h for the room and roof space, respectively. Moisture storage or diffusion in the construction elements is not included in the heat and moisture transfer algorithm. [6]

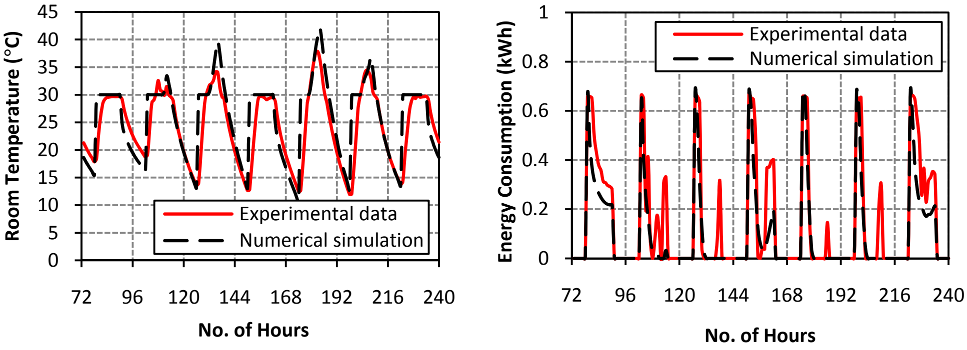
2.4 Validation

The test room temperature and energy consumption for the last 7 days of the heating period experiment were compared with the numerical simulation results. As shown in Figure 3 and Figure 5, the numerical model produced good predictions of the room temperature for the free-floating period in May. For the heating period, there are more deviations between the numerical and experimental results, which could be explained by two reasons. Firstly, there is a time lag between the instances when the radiator is switched on/off and when it actually reaches its working temperature/cools down. This is not considered by the numerical simulation, and therefore results in the instantaneous rise (at 6am) and drop (at 6pm) of the room temperature (Figure 4-a). Secondly, since the efficiency of the electric radiator is unknown, the numerical analysis is carried out assuming an efficiency of 100%. This explains why the area below the experimental data curve is larger than the area below the numerical data curves (Figure 4-b). Nevertheless, R^2-values shows a very good agreement between experimental and numerical energy consumption (Figure 5), which is of primary interest and will be used for further investigation.



(a) (b)

Figure 3: Comparison of experimental and numerical simulated room temperature of Room 1 (double glazed) in (a) The free-floating period, and (b) The heated period in October (right).



(a) (b)

Figure 4: Comparison of experimental and numerical simulated (a) room temperature (b) energy consumption of Room 1 (double glazed) in heated period.

Room No.	**Glazing type**	**May**	**Oct**	
		Room temperature	**Room temperature**	**Energy consumption**
1	Double glazing	0.987	0.576	0.995
3	Opaque	0.825	0.643	0.999
5	Single glazing*	0.978	0.651	0.996

Figure 5: Goodness of fit (R^2-values) between numerical simulation and experimental data. * For the heated period in Oct the glazing type is double glazing with half the area of the double glazing for Room 1.

3 Investigation of high-performance façade technologies

3.1 Modification from the preliminary model to a typical office model

In order to obtain results more close to a real-world senario, the EMC room model was modified to represent a typical office room located in London. It is assumed that only one surface of the room is exposed to the external environment, while the other surfaces are adjacent to ambient rooms which have the same thermal condition with the simulated room and are therefore assumed to be adiabatic. The U-values of the exposed wall is improved to 0.35W/m^2·K to satisfy the requirements of Building Regulations for England and Wales [7]. The cooling and heating set points are 24°C and 20°C, respectively. The air infiltration is assumed to be 8ac/h.

The internal gain from people, artificial lighting, and equipment is as follows: the office is assumed to be occupied by one person with an activity level of 125W/person; the fluorescent lighting is 150W; the luminaire configuration is 18% visible and 72% radiant; the electric equipment design level is 192W. Daylighting control is applied in this model. The reference point is 1.0m away from the window and 0.8m above the floor level. The illuminance setpoint is 500lux, which means that when the illuminance is above 500lux, the artificial light will be dimmed gradually to maintain 500lux.

An annual simulation is carried out to explore the effect of varying the window to wall ratios from 25% to 100% with the assumption that the facade faces south. The effect of orientation is also investigated.

3.2 Study cases of high-performance façade technologies

Eight study cases were investigated by changing the window construction for the modified model. Each case contains only one façade technology. The objective is to see how each type of technology affects different components of energy consumption, i.e. heating energy, cooling energy, and lighting energy.

Case 1 - Basic office (DG): The window is double glazing with a U-value of 2.5W/m^2·K. The construction is 13mm argon between two 6mm clear glass panes. No shading devices are provided. The other cases use this as a base model – all the variables are kept unchanged except for those restated.

Case 2 - Opaque wall (OW): This case simulates a windowless chamber.

Case 3 - Double glazing with low-e coating (DGLE): The emissivity of the internal surface of the outdoor facing glass pane is reduced from 0.84 to 0.1.

Case 4 - Triple glazing (TG): The window is triple glazing with a U-value of 1.6W/m^2·K, which is composed of three 3mm clear glass panes with 13mm argon layers in between.

Case 5 - Vacuum insulation glazing (VIG): The performance properties of VIG are taken from SPACIA-ST SE8 produced by Nippon Sheet Glass Spacia Co.,LTD, i.e., [9]. The visible transmittance is 0.746, the solar heat gain coefficient is 0.74, and the U-value is 1.5W/m^2·K.

Case 6 - Electro-chromic glazing (ECG): Switchable shading control is added to Case 1. The properties are taken from EnergyPlus database as follows: the solar transmittances are 0.814 for the bleached state and 0.111 for the coloured state; the visible transmittances are 0.847 for the bleached state and 0.128 for the coloured state. It provides shading when the room temperature reaches 23°C.

Case 7 - PV integrated double glazing (PV): The performance properties are taken from one of SHOTT AG's products – ASI THRU® double-glazed unit [10]. The solar heat gain coefficient is 0.1, the U-value is 1.2W/m^2·K, and the visible transmittance is 0.1. The solar cell efficiency is 7%.

Case 8 - Suspended particle devices (SPD): The performance properties are taken from SmartGlass International's SPD-SmartGlass™ [8]. The U-value is 0.24W/m^2·K, the solar heat gain coefficients are 0.39 for the on (clear) state and 0.33 for the off (dark) state. The visible transmittances are 0.22 and 0.01 for the on (clear) state and off (dark) state, respectively. The set point temperature for the on/off state is set at 23°C.

3.3 Results and discussion

The results for energy consumption and generation are calculated using the modified model and shown in Figure 6. Cost of different energy resources is ignored, since this varies from region to region and can always be included to suit a particular scenario. Glare is not considered in this study.

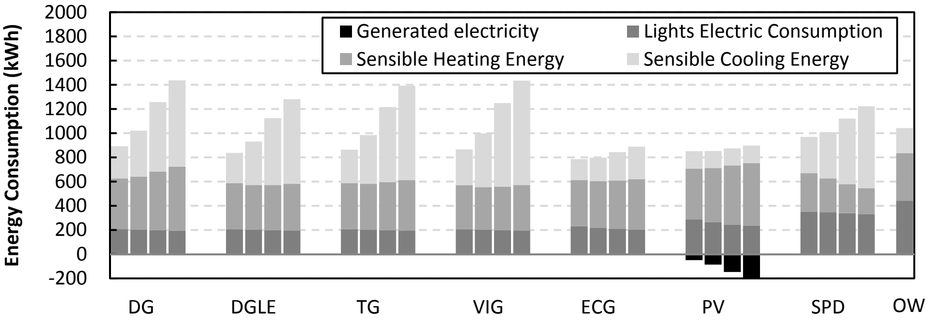


Figure 6: Components of energy consumption/generation of alternative technologies used on facades facing south. (The four bars for each technology represent scenarios when window to wall ratios are 25%, 44%, 75% and 100% from left to right.)

Figure 6 shows that, after adding low-e coating to double glazing, heating energy was reduced by 5%-20%. TG and VIG improve the U-values and therefore save 10%-30% of the heating energy. On the other hand, the cooling energy is increased by 10%-20%, when the window to wall ratio is larger than 75%. Therefore, when window to wall ratio is large and cooling energy is dominating throughout the whole year, it is not energy efficiency to try to achieve a U-value as low as possible, except for the situation when internal temperature is lower than external temperature. ECG and PV consume much less cooling energy especially when the window to wall ratio is relatively high, but they reduce the view-out. SPD does not provide much shading, because it absorbs solar radiation, which is partly emitted back into the room. The opaque wall requires the largest amount of lighting, while keeping cooling energy at a low level. When the window to wall ratio is less than 44%, it is more energy efficient to have glazed opening compared to opaque wall.

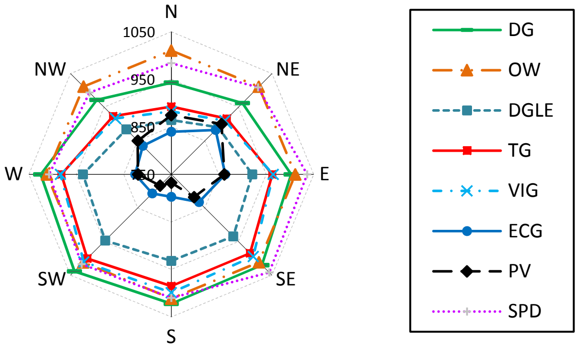


Figure 7: Net energy consumption of alternative façade technologies for different orientations (kWh)

Keeping the window to wall ratio at 44% as the original model in Figure 2, the effect of orientation was then investigated. Figure 7 provides a ranking of the eight cases when the modified model is rotated to face the external wall to different orientations while keeping the other surfaces adiabatic. ECG and PV are generally superior to other technologies in terms of net energy consumption, especially when applied on the south facing façade. Therefore, it is recommended to provide shading control and active solar control, especially when the façade faces south. DGLE, TG, and VIG are comparable with PV when installed on the north and north east façades, which means that a good solution for façades facing these directions is to reduce the U-value.

4 Conclusion and Future Work

A validated thermal performance analysis model of a typical office was constructed using EnergyPlus. A parametric study has shown that electro-chromic glazing and PV integrated glazing are less sensitive to window to wall ratio, and are superior to other technologies in terms of net energy consumption, especially when installed on south and west facades.

Some important quantitative conclusions can be drawn on the relative performance of the alternative façade technologies, and the good fit between experimental results and the numerical model are essential for the planned further development of this approach. The limitations are that some other important performance criteria of façade such as embodied energy, aesthetics, variable natural ventilation, and detailed occupant comfort are ignored. Moreover, all the conclusions are based on a simple office model and investigations into one façade technology at a time, which is already very laborious. It is therefore desirable to develop an automated multi-objective selection and design optimisation tool that integrates whole-life value design criteria and is capable of considering possible combinations of high-performance façade technologies, different orientations and locations simultaneously.

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