IMPACT OF THE CONTROL OF SHADING DEVICES ON THE THERMAL BEHAVIOUR OF LARGE HIGHLY-GLAZED SPACES

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ABSTRACT

Evidence suggests that a significant number of large highly-glazed spaces have major design flaws that lead to energy wastage and discomfort. Provision to control solar gains are generally insufficient in these buildings, which can lead to excessively high temperatures during the summer. Besides, the solutions implemented to overcome these issues usually have a high energy cost, whereas passive techniques may well limit these problems.

This paper deals with design issues related to solar protections. The objective of this work is to derive and implement methods to evaluate the impact of design parameters - such as solar transmission of windows, presence and control of shading devices - on the thermal comfort in large highly-glazed spaces. For this, sensitivity analyses were performed on the comfort of an attached-atrium building. The simulations were performed with AIRGLAZE (Voeltzel et al., 2001), a research code developed specifically to predict the thermal and ventilation behaviour of large highly-glazed spaces.

Our results stress the key role of shading devices and quantify their effect on the operative temperature in the occupied zone. The impact of the control of the shading devices appears to be modest in summer conditions compared to an adequate design of fixed protections.

KEYWORDS

Large highly-glazed spaces, Atria, Sensitivity Analysis, Factorial design of experiments, Control, Shading device

INTRODUCTION

Large highly glazed spaces, such as atria, have become more and more popular during the last decades. They open virtually the building to the outside, while protecting the occupants from the outdoor climate (Bryn, 1995). This sociological feature is very important for the architects who are usually concerned about the symbolic meaning of different design alternatives.

However, despite the technology progress on the optical and thermal properties of glass, most of these spaces appear to have major design flaws that lead to considerable energy wastage and discomfort. In fact, Voeltzel et al. (2001) estimated that the energy consumption (normalised by floor-area) of such service buildings lies in the region of 250 to 300 kWh/m^2 per year, whereas with good design it is reasonable nowadays to aim for energy consumption lower than 150 kWh/m^2 per year. Furthermore, energy-expensive remedies using active cooling strategies are more and more considered by designers although they can rarely overcome the violation of simple design rules regarding, for example, the ventilation or the solar protections.

One major reason for these design problems certainly lies in the complex thermal behaviour of these large sunpaces. There exist few field studies on the subject and the existing simulation tools and design methods are generally inadequate (Prommer, 1995; Voeltzel, 1999). Therefore, professional experience in this field remains insufficient, which often leads to errors in the estimation of trends in thermal comfort.

This study aims to further explore the thermal behaviour and design of large highly-glazed spaces, by evaluating the impact of design parameters on thermal comfort. Therefore, we have performed on a test case (a) a screening on 11 design parameters to determine those that have a major impact, (b) a sensitivity analysis on the prevalent parameters and, (c) a sensitivity analysis to measure the impact of the control of a shading device.

METHODOLOGY

Test Case

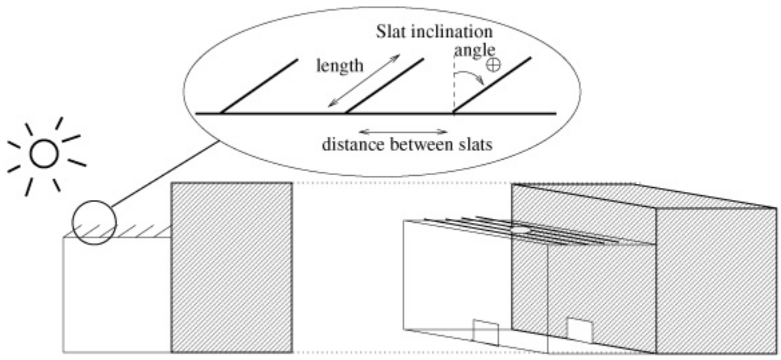

Figure 1 : Attached large highly-glazed space with a control device and an extractor

The simulations were performed on the case of an attached sunspace (15-m large and 30-m long) with an extract fan under the glazed ceiling and two openings on the ground level. The adjacent space is air-conditioned. Its temperature is set at 23°C from 8 a.m. to 6 p.m., and night ventilated.

The shading device on the ceiling, used for the evaluation of the control, is formed by slats with a length of 330 mm, the same as the distance between the slats. The reflectance of the slats is of 85%, half specular and half diffuse. The slat angle for the fixed shading device was chosen to optimise the ratio of the daily average diffuse transmittance to the daily average direct transmittance, both given by GLSIM-BLIND (Pfrommer, 1995). We allowed 15% of average daily direct transmission, and therefore chose an angle of 50° to maximise the diffuse transmission.

For the control strategy of the mobile shading device, we chose to tilt the slat according to the sun position, so that the daily direct transmission is about 15% while maximising daily diffuse transmission. A test is performed every five minutes on the horizontal illuminance I_{dh} to determine if the sky is cloudy, in accordance with the method proposed by the World Meteorological Organisation (WMO, 1983). If equation (1) holds, the sky is considered cloudy and therefore the shading device is opened with a slat inclination of –20°, corresponding to the maximum SW total transmittance.

$$\frac{I_{dh}}{\cos\beta} < 120W/m^2 \quad (1)$$

with β the sun elevation (rd).

Factorial Design of experiments

Design of experiments allows one to organise the simulation runs in order to retrieve maximum information with a minimum of simulation runs. This implies some assumption or knowledge of the behaviour of the responses to the factors. Here, we assume a linear response to each factor taken individually. With simple arithmetic calculation, it allows us to compare simultaneously the effect and interaction of both qualitative and qualitative factors. We used the factorial design and the factorial fractional design of experiments methods with two extreme levels for the factors, marked below as –1 and +1 (Montgomery, 1997).

Thermal comfort Criteria

Our thermal comfort criteria are based on the operative temperature T_{op}, as defined in ISO standard 7730 (1995). In addition to the operative temperature at 3 p.m. in the occupied volume or to the mean operative temperature from 9 a.m. to 16 p.m. in the occupied volume, we used the average of the temperature deviation I from the comfort zone [23-26°C] in the occupied volume, defined by equation (2).

$$I = \frac{1}{h_1 - h_2} \int_{h_1}^{h_2} f(T_{op})\, dh \quad (2)$$

where $\begin{cases} f(T_{op}) = 0 & if\ 23 \le T_{op} \le 26°C \\ f(T_{op}) = \left|\max\left((T_{op} - 26),(23 - T_{op})\right)\right| & if\ T_{op} < 23°C\ or\ T_{op} > 26°C \end{cases}$

and T_{op} is the operative temperature in the occupied volume (°C), I is the average of the temperature deviation (°C), and $h_1 = 9$ hours, $h_2 = 16$ hours are the time limits in hours.

Simulation Tool

The simulation tool used, AIRGLAZE (Voeltzel, 1999; Voeltzel, 2001), consists of an envelope module to calculate conductive and radiative heat transfer in the building envelope. It is coupled with a network-based (zonal) airflow model to predict air motion within the room. Particular attention is paid to sun patch modelling and the internal distribution of shortwave (SW) and longwave (LW) radiation within the building -direct retransmission, reflection to the outside, and transmission to other zones of the building- are taken into account. Fixed and mobile shading devices have been implemented using the angle dependent transmittances and absorption values given by GLSIM-BLIND developed by Pfrommer (1995). The calculation of these values considers the inter-reflections between the slats and between the glass panes and the slats. The incidence angle dependent transmittance through a glazing behind a blind is treated by considering the effective incidence angle of both the directly received radiation and the reflected radiation from the slats (Pfrommer, 1995).

PREVALENCE OF SW TRANSMITTANCE

The screening was performed with a factorial fractional design 2^{11-7} (16 simulations) on the 11 factors, listed in TABLE 1.

TABLE 1
Factors levels for the screening on an attached highly-glazed space without the external blind

	Factors	-1	1	
x_{ar}	Air change rate	0.5	5	ach
x_{tw}	Adjacent wall thickness	15	25	cm
x_{tf}	Floor thickness	15	25	cm
x_O	Orientation	north	south-east	-
x_{SW}	SW transmittance	2.8	1.9	-
x_H	Height	8	20	m
x_U	Glass U-value	8	20	W m^{-2} K^{-1}
$x_{\lambda w}$	Adjacent wall conductivity	0.18	1.8	W m^{-1} K^{-1}
$x_{\lambda f}$	Floor conductivity	0.18	1.8	W m^{-1} K^{-1}
$x_{\rho Cw}$	Adjacent wall ρC*	502200	1567200	J m^{-3} K^{-1}
$x_{\rho Cf}$	Floor ρC*	502200	1567200	J m^{-3} K^{-1}

* ρC is the product of the wall density by the heat capacity

All comfort criteria consistently and logically showed that the prevalent factors were the SW transmittance of the glass and the air change rate, followed by the height of the space and the conductivity of the floor, as illustrated in Figure 2. The Pseudo Standard Error calculated as in Lenth (1989) after having retrieved the four prevalent factors, indicate that the effects weaker than 4°C can be considered as noise.

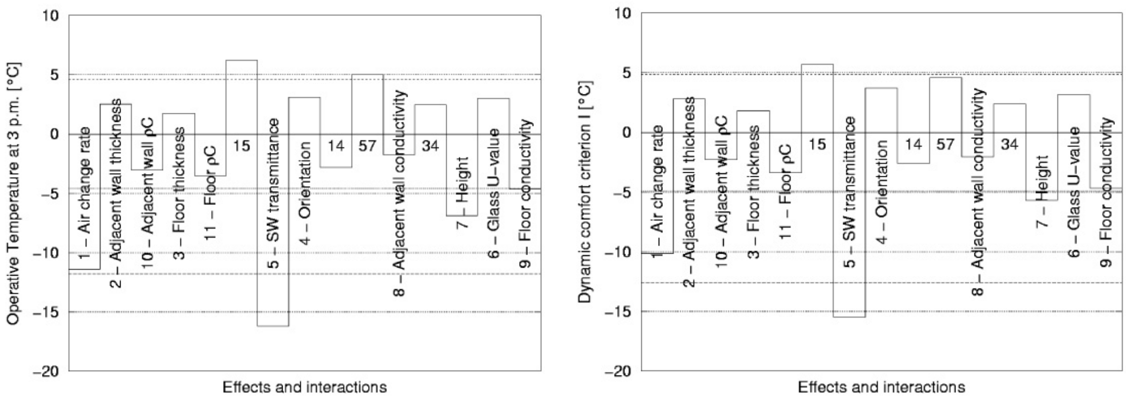

Figure 2 : Effect and interaction for the screening. The effects and interactions are labelled on the x-axis. The bar corresponding to each effect or interaction represents the variation of temperature between the level –1 and +1 of the factor considered.

The similarity of the effect for the operative temperature at 3 p.m. and for the dynamic criterion I (cf. Figure 2), as well as the negligible impact of the product of the wall density by the heat capacity (ρC), show the insignificance of thermal inertia in this case. The impact of height can be explained by the thermal stratification that occurs in the large highly-glazed space. The interaction between height and SW transmittance is due to the fact that the glass surface area increases with increasing height. The interaction between air change rate and SW transmittance moderates the simultaneous impact of both factors: when air change rate increases in a space with low SW transmittance, it has a lower effect than in a space with average or high SW transmittance.

SIMPLIFIED MODEL OF THERMAL BEHAVIOUR

A factorial design of experiments allowed us to obtain a polynomial that is linear with the respect to each factor taken individually. For the four prevalent factors found in the screening procedure, a complete factorial design leads to equation (3) for the operative temperature at 3 p.m. Additional simulations showed an error in the estimation of the temperature in °C of about 10%, but good agreement between the tendencies. Therefore, the model can be used as a guidance to estimate the tendencies on the operative temperature of different design options, as illustrated in Figure 3.

$$\hat{y} = 32.05 + 59.79x_{SW} - 0.37x_{\lambda f} - 1.08x_{ar} - 0.05x_H - 1.30x_{SW}x_H - 3.29x_{SW}x_{ar} - 6.17x_{SW}w_{\lambda f} \quad \textbf{(3)}$$

where $\hat{y}$ is the estimation of the response, i.e. the operative temperature at 3 p.m., and the symbols x_{indice} are defined in TABLE 1.

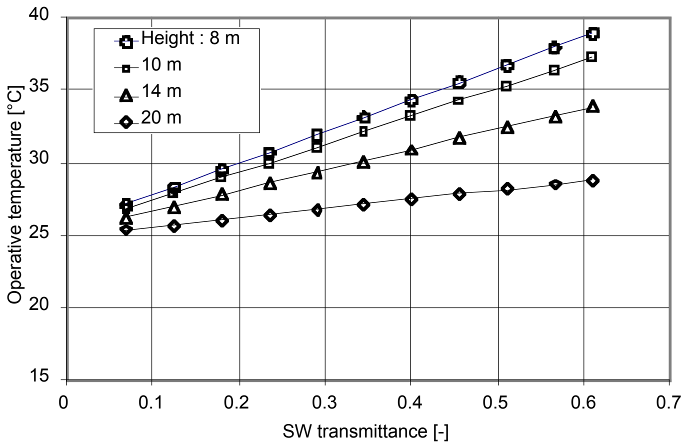

Figure 3 : Operative temperature at 3 p.m. according to SW transmittance and height of an attached highly-glazed space.

IMPACT OF THE SLAT TILTING'S CONTROL

A sensivity analysis was performed with factorial design of experiments on the presence of slat tilting control and on the three other prevalent factors (floor conductivity, air change rate, and height) for two types of day : sunny (21 June 1998) and cloudy (11 June 1998).

For the sunny day, the impact of the control is weak, especially compared to the effect of air change rate. If anything, it seems to be detrimental to comfort, probably because the mean direct transmittance is slightly higher (about 20%) than the one for the fixed slats (15%). An analysis of variance showed that, for a sunny day, the effect of control is significant, but has only a contribution to the mean operative temperature from 9 a.m. to 16 p.m. from 8.5% (cf. TABLE 2). This can be explained by the fact that only the glass ceiling is protected. For a cloudy day, the impact of control on the mean operative temperature is negligible (cf. Figure 4). This was predictable as the solar radiation is low.

TABLE 2
Analysis of variance for the mean operative temperature from 9 a.m. to 16 p.m. the 21th of June 1998

Identifica-tion	Effect	Associated variance	Degrees of freedom *ddl*	Mean square *MS*	Fisher-Snedecor statistic *F*	Associated probability *p*	Contribution %
1	1.79	50.99	1	50.99	15.35	2.40E-03	8.5
2	-2.30	84.80	1	84.80	25.52	3.71E-04	14.2
3	-4.80	368.67	1	368.67	110.97	4.39E-07	61.8
4	-1.86	55.63	1	55.63	16.74	1.78E-03	9.3
Remainder	0.01	36.55	11	3.32			6.1
Total	-7.17	596.64	15	563.42			100.0

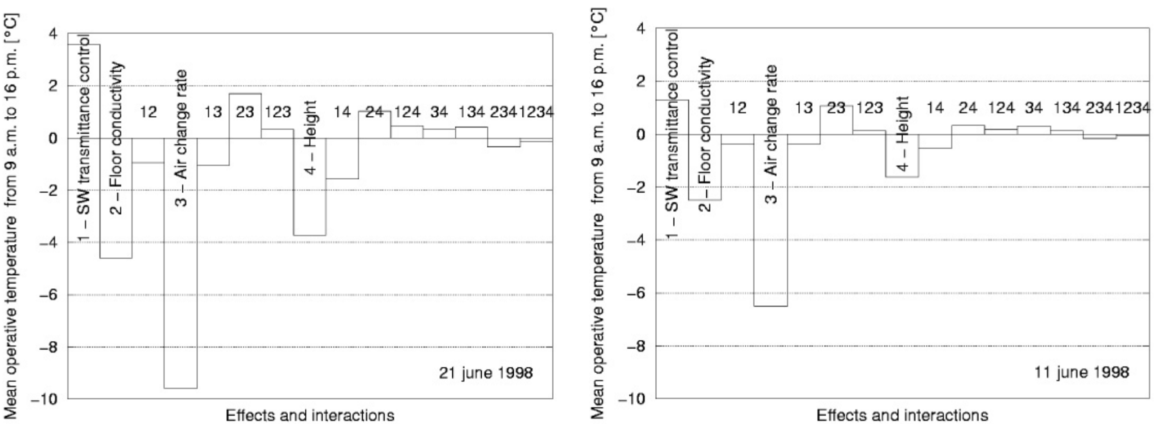

Figure 4 : Effect and interaction for the attached highly-glazed space with external blinds on the glass ceiling

CONCLUSION

Sensivity analyses with factorial design of experiments showed, with few simulations, the prevalence of SW transmittance and air change rate for an attached large highly-glazed space within the 11 factors retained and quantified their effect and interactions. We also obtained a simplified model of its thermal behaviour, that showed good agreement for estimating tendencies and comparing various design options. An investigation of the control of shading devices showed that the control strategies used have a modest impact on thermal comfort. In the case investigated, this study suggests that 'fixed' slats, whose position can be changed with the season, can be as efficient as controlled slats.

REFERENCES

Bryn, I. (1995). Atrium buildings from the perspective of function, indoor air quality, and energy use. *ASHRAE Transactions.* **101 : 2**, 829-840.

ISO 7730 (1995). *Ambiance thermiques modérées - Détermination des indices PMV et PPD et spécifications des conditions de confort thermique*. CD-reef version 115 (03/1999). CSTB, France.

Lenth, R. (1989). Quick and Easy Analysis of unreplicate factorials. *Technometrics*. **31: 4**, 469-473.

Montgomery, D.C. (1997). *Design and analysis of experiments*. 4th ed. John Wiley &Sons, New-York, USA.

Pfrommer, P. (1995). *Thermal modelling of highly glazed spaces*. Ph-D: De Montfort University, Leicester, UK.

Voeltzel, A. (1999). *Modélisation du comportement thermoaéraulique des grands volumes vitrés en régime dynamique*. Doctorat: Conception en bâtiment et techniques urbaines, Institut National des Sciences Appliquées de Lyon, France.

Voeltzel, A., Carrié, F. R., Guarracino, G. (2001). Thermal and Ventilation Modelling of Large Highly-Glazed Spaces. *Energy and Buildings*. **33**, 121-132.

World Meteorological Organization (1983). *Guide to meteorological instruments and methods of observation*. 5th ed. Genève, Suisse.