VENTILATION AND COOLING
18TH ANNUAL AIVC CONFERENCE
ATHENS, GREECE, 23-26 SEPTEMBER 1997

ok

Title: On the ventilation and daylight efficiency of various solar shading devices

Authors: A. Tsangrassoulis, M. Santamouris, D. Asimakopoulos

Affilitation: Group Building Environmental Studies, Physics Dept., University of Athens, University Campus 15784, Athens, Greece.

Bedoeling integreren in thermisch model ...

(1) Test cell experiments

Passys Cell → ≠ openingen

≠ shading devices

(2) Daylight coefficients

↳ backw. ray-tracing

Δ rer-meas = 30% à 18% o.k.

(3) Ventilatie

→ network (methode Mat)

→

ON THE VENTILATION AND DAYLIGHT EFFICIENCY OF VARIOUS SOLAR SHADING DEVICES

A. Tsangrassoulis, M. Santamouris and D.N. Asimakopoulos

Group Building Environmental Studies
Physics Department, University of Athens, Panepistimioupolis, 157 84, Athens, Greece.

Synopsis
Solar control devices placed in front of large building openings disturb air flow and the radiation transfer. Although solar radiation transfer through obstructed openings is a relatively well researched area, very little information is available regarding the air flow perturbations and daylighting alterations created by external solar control devices. The present paper reports a series of experiments aiming at investigating natural ventilation and daylight phenomena associated with the use of specific shading devices. Experiments have been carried out in outdoor test cells and twenty eight different configurations have been tested for several window characteristics under various climatic and radiation characteristics. Based on the experimental results, specific modeling activities have been undertaken and theoretical methods of calculating air flow and daylight through openings equipped with specific solar control devices have been developed and are now presented. Theoretical predictions are compared with the corresponding experimental data and a very satisfactory agreement has been found for both air flow and daylight processes.

List of symbols
C(t) gas concentration at time t (ppm)
λ air changes per time unit
L_k is the luminance of the kth sky patch (cd/m^2)
a_k is the solid angle of the kth sky patch (sterad)
d_k is daylight coefficient of the kth sky patch ()
ρ density (kgr/m^3)
Q air flow rate (m^3/sec)
C_d discharge coefficient
A area of the opening (m^2)
Ar_D Archimedes number
Gr Grashof number
Re Reynolds number
g acceleration of gravity (m/sec^2)
H opening's height (m)
D depth of the test room (m)
T temperature (^{0}K)
U air speed (m/sec)

1. Introduction
Buildings are one of the most important energy consuming sectors. In Europe, buildings represent almost forty percent of its global energy consumption. A very high percentage of the consumed energy is used to cover both the cooling and the lighting needs of buildings as well. The shading effects of fixed and movable shading devices have been extensively studied, and very accurate models for their performance have been developed under dynamic or steady state conditions [1]. However, the impact of solar control devices on the airflow through obstructed openings is relatively poorly researched, while the existing knowledge on the air flow regime as well as on the

combined air flow and radiation transfer through openings equipped with solar control devices, is very limited [2]. In reality, phenomena of air flow through large openings are of a random nature and this because of the wind characteristics. Thus the proposed models should be designed to allow calculation of the air flow through the obstructed openings when the main climatic and geometrical characteristics are known.
Modelling of the performance of the louvers, as it concerns daylighting, can be performed by using empirical or flux transfer methods, [3], radiosity based methods, [4], or ray tracing techniques, [5]. Radiosity based models can treat only diffuse surfaces and present problems with highly reflected materials. Furthermore due to the need of accurate calculation of the form factors a high memory capacity is required in order to take into account detailed scenes such as an aperture equipped with blinds. Ray tracing techniques solve the rendering equation, [6], under most conditions including specular and diffuse reflection and transmittance in complicated curved geometries. However, as internal illumination has to be calculated in a dynamic way to take into account sky variability, these models require a very high computational effort and this because intereflection calculations have to be performed for each time step. Thus, there is a need for models that can calculate, in an accurate way, illuminance levels in complicated geometrical environments without to repeat time consuming intereflection calculations at every time step.
This paper presents the results of a series of 28 different experimental configurations where various shading devices have been tested in a real scale outdoor facility. It also presents appropriate theoretical models to evaluate air flow and daylight transfer through the studied solar control devices.

2. The Experimental Set Up

In order to expand existing knowledge on the physical phenomena related to the impact of movable solar control devices associated with large building openings a series of experiments have been carried out in a PASSYS test cell, [7]. Particularly, the experiments aimed to evaluate processes related to the air flow and daylight transfer through the openings under single side ventilation configurations. The PASSYS test cell is a fully equipped, two zones, outdoor facility for thermal and solar monitoring. Wall temperature, internal and external air temperature, internal and external (diffuse and global) illuminance, wind speed and direction were measured continuously in 2 min intervals. During the experiments and in order to estimate the luminance distribution of the sky, a luminance camera (Minolta LS-101) has been used to perform sky scanning. This procedure was based on the pattern recommended by the CIE [8], on 145 patches in 12 degree bands of altitude, centered in azimuth on the solar azimuth. The south facade of the cell is removable and allows installation and testing of specific building components. Experiments were carried out in the "test room" while the door connecting it to the "service room" was kept closed and sealed. The test room has a height of 2.72 m and a volume of 35 cubic meters.
To study the impact of the opening surface especially on the air flow through the obstructed window, a specific component has been constructed and attached to the removable south facade of the cell. The component covers the whole facade of the cell and has a transparent surface - opening of 4 m^2 located at the center of the facade. The maximum height and the width of the opening are equal to two meters. The opened area

of the component is adjustable in order to perform experiments under various opening surfaces. Two type of shading devices have been tested and in particular, movable vertical and horizontal louvers. The louvers are made from metallic sheets having a mat white finish of 0.1 m in width and 2 m in length. Experiments have been performed for various tilt angles of the louvers and various opening areas. Table 1 present the main characteristics of the experiments.

No	Area of the Opening, m^2	Type of Shading Device	Tilt of Louvers
1	0.5	Horizontal louvers	0^0
2	1	Horizontal louvers	0^0
3	2	Horizontal louvers	0^0
4	4	Horizontal louvers	0^0
5	0.5	Horizontal louvers	60^0
6	1	Horizontal louvers	60^0
7	2	Horizontal louvers	60^0
8	4	Horizontal louvers	60^0
9	0.5	Horizontal louvers	30^0
10	1	Horizontal louvers	30^0
11	2	Horizontal louvers	30^0
12	4	Horizontal louvers	30^0
13	0.5	Vertical louvers	45^0 east
14	1	Vertical louvers	45^0 east
15	2	Vertical louvers	45^0 east
16	4	Vertical louvers	45^0 east
17	0.5	Vertical louvers	0^0
18	1	Vertical louvers	0^0
19	2	Vertical louvers	0^0
20	4	Vertical louvers	0^0
21	0.5	Vertical louvers	45^0 west
22	1	Vertical louvers	45^0 west
23	2	Vertical louvers	45^0 west
24	4	Vertical louvers	45^0 west
25	0.5	No Shading	
26	1	No Shading	
27	2	No Shading	
28	4	No Shading	

Table 1. Main geometrical characteristics of the experiments.

Ventilation experiments were performed using a single tracer gas decay method. N_2O was used as tracer gas. Injection and sampling points were carefully chosen in order to achieve the necessary homogeneity. The sampling period was set to 30 sec. Tracer gas concentration was measured by an i.r. gas analyzer.

During the experiments N_2O was injected in the room, while the exterior opening was sealed. Small fans were used to enhance good mixing of the gas during the injection period. When the gas concentration reached the required levels and mixing was satisfactory, fans were turned off, the injection stopped and the window opened.

According to the decay method the decrease of the tracer gas concentration is given by the following equation:

$$C(t)=C(t0)\exp(-\lambda t) \qquad (1)$$

where C(t) and C(t0) are the tracer gas concentrations at time t and at t=0, respectively. The air changes per hour have been calculated for each sampling point and then the mean value for the whole room was calculated as the mean of all sampling points.

3. **Daylight Results and Modeling**

The developed method uses the Monte Carlo approach, a kind of backward ray-tracing in order to calculate the daylight coefficients. Daylight coefficient [9] is defined as the ratio between the luminance of a patch of sky and the illuminance in the building due to light from that patch.

The sky can be divided into zones of altitude and azimuth and the daylight coefficient can be found at each zone. Then total illuminance, at one point in a room, can be calculated using the following equation:

$$\text{Illuminance} = \sum_{k=1}^{\text{number of sky patches}} Lk\ ak\ dk \qquad (2)$$

where L_k is sky luminance, a_k is the subtended size of a sky patch and d_k is the daylight coefficient.

Following the daylight coefficients approach, the intereflection calculation is carried out once for each zone, and it doesn't have to be repeated if the sky luminance distribution changes. The advantage of this approach is that hourly calculations of interior lighting in a building, for a whole year, can be performed faster without repeating intereflection calculations. Additionally, because the sky is treated as a number of point sources, the contribution of direct and reflected sunlight in the interior lighting could easily be assessed by adding, to the sky zone where the sun is located, an additional luminance equal to the normal solar illuminance divided by the solid angle of the zone. Each emitted ray has an initial weight equal to 1. After each reflection or transmission the ray weight is multiplied by the corresponding reflectance or transmitance of the surface. If the resulting value is larger than a predefined threshold value the whole procedure is repeated; in the opposite case, the ray is considered to be absorbed. This developed method can deal with a large variety of reflection models. Particularly, the method considers specular, diffuse, specular and diffuse, reflective and diffusing glass. The model considers the ground as a separate surface with reflectance equal to 0.2. For all rays that do intersect with the ground a single ground reflected daylight coefficient is calculated.

The accuracy of the developed simulation method is affected by : a) the number of initial emitted rays, where the standard error regarding the estimation of the illuminance is inversely proportional to the number of emitted rays, and b) the limit value of ray-weight. This last variable affects the intereflection component of illuminance. Lower value contributes to higher intereflection values.

Twenty five thousand initial rays have been used by the present model, while the threshold ray weight has been considered equal to 0.1 The ratio of this threshold value to the average reflectance of the area is equal to the mean number of light bounces. For our experiments, the area weighted reflectance of the test cell was approximately equal to 0.4 thus, four light bounces have to be expected in average.

After the quality control tests twenty one data sets measured during June 1996 and September 1996 have been considered. Then for each specific experiment, simulations have been performed using the developed model. Finally, the calculated and measured data have been compared for both indoor measurement points.

Mean differences between predicted and measured values are close to 13 % for the first measuring point and to 18 % for the second one. Higher differences are observed for point two because the local illuminance is reduced as louvers reduce the area of visible sky. Consequently, intereflections have a much higher contribution to the horizontal illuminance at points away from the window, and this is a source of computational error. Differences are smaller when no shading devices are used. In this case there is no redirection of light by the shading devices and thus intereflections are not important. Maximum errors are observed in configurations combining small surface openings and shading devices. The error of internal and external illuminance measurements is estimated close to 10%. The main source of error is the procedure of estimating the sky luminance distribution. As already mentioned, the time period for a complete sky scanning was 15 minutes. In order to reduce the error, two measurements of zenith luminance have been performed one at the beginning and the other one at the end of a scanning session. When the variance between both values was higher than 25% the data set was rejected. The scanner's acceptance angle was 1^0 so each point measurement is assigned practically to a sky patch, offering a small sky coverage. Errors associated with the model are of a random nature. The initial number of emitted rays is used to sample a continuous environment, resulting in an underestimation of the predicted illuminance. Furthermore, the number of the used light bounces is limited in comparison to infinite light bounces of real world. Increasing the number of rays and decreasing the threshold ray weight, predictions are improved, but the computational time increases.

4. Ventilation Results and Air Flow Modeling

Calculation of the air flow through large building openings can be achieved either by using empirical, network or computerized fluid dynamic models, [10]. Empirical models are in general of local validity, while do not take into account effects related to solar control devices. Computerized fluid dynamic, CFD, models are powerful tools, but are not so suitable for natural ventilation configurations, [11]. CFD tools are extremely sensitive to the initial and boundary conditions, which in natural ventilation studies are of a random nature and not well known.

Network prediction models are based on the mass flow balance of a space

$$\sum_{i_m=1}^{j_m} \rho_{im} \cdot Q_{im} = 0 \qquad (3)$$

and combine the effect of wind and buoyancy to calculate pressure differences. Network models have been proved to provide very reasonable predictions of the air flow levels in natural ventilation configurations, [12]. In equation (3), Q_{im} is the volumetric flow rate through the ith flow path of the mth node and ρ_{im} is the density of air flow through the ith flow path of the mth node (kg/m3).

The air flow through an opening is calculated by using the standard orifice equation :

$$Q = C_d \cdot A \cdot \sqrt{\frac{2 \cdot |\Delta P|}{\rho}} \quad (m^3/sec) \qquad (4)$$

where Cd is the discharge coefficient of the opening, A is the flow area, ΔP is the pressure difference across the opening and ρ is the air density.

For large non obstructed openings, discharge coefficient varies between 0.6 and 1. An extensive review of the existing methodologies to calculate the discharge coefficient of large non obstructed internal openings is given by Santamouris et al. [13]. However, no methodologies have been developed to calculate discharge coefficients for large openings equipped with solar control devices.

A network air flow model, developed especially for natural ventilation configurations, [14], has been used to calculate the air flow for all the studied configurations. All calculations have been carried out using a discharge coefficient equal to one.

As it was expected the agreement between the experimental values and the results given by conventional network air flow model was not satisfactory. This conclusion agrees with results given by Dascalaki et al, [15], for single sided natural ventilation experiments carried out under quite high wind speeds. As found predictions can be highly improved if the relative importance of the inertia and gravitational forces is considered appropriately. It is found that the prediction error is proportional to the Archimedes number. Based on this, a new parameter CF has been proposed to be used to correct predictions of the network models, [15]:

CF = Measured Air Flow / Predicted Air Flow.

In the above mentioned paper it was found that CF can be expressed as an expotential function of the Archimedes number (Ar_D). Based on the above analysis an attempt has been made to study whether the observed differences between experimental and predicted values can be correlated with the Archimedes number:

$$Ar_D = \frac{Gr}{Re^2} = \frac{g \cdot H^3 \cdot \Delta T}{T \cdot U^2 \cdot D^2} \quad (5)$$

gebaseerd op methode Hat Santamouris

Figure 1 shows CF values versus Archimedes number in the case of horizontal louvers with 30 degrees tilt.

afh. v/d configuratie v/h gebouw

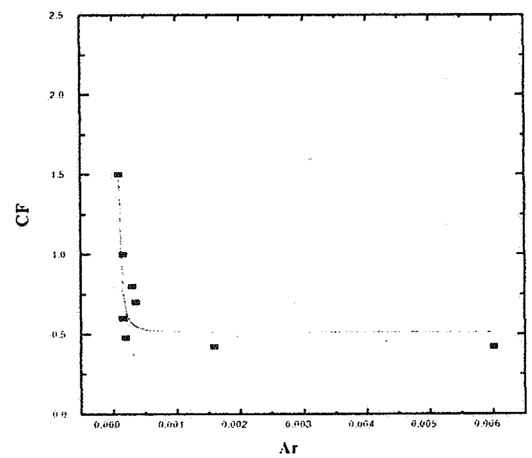

Fig.1 Measured/Predicted values of air flow rates versus Archmedes number

As shown, there is a very good agreement between the ratio of the measured to the predicted air flow (CF) and the Archimedes number. Based on the obtained results expressions to estimate CF, as a function of the Archimedes number have been obtained. For the case of horizontal louvers, it is found that Lorenzian type equations fit better the results :

$$CF = (2\ A1\ w1/3.14)/(w1^2+4(Ar-x_c)^2)+y_0 \qquad (6)$$

The obtained coefficients for equation 6 and for the various tilt angles are given in Table 2. The obtained correlation coefficients are given as well.

Shading	A1	w1	x_c	y_0	Correlation Coefficient
No	4.25E-4	4.48E-5	-1.24E-5	0.88	0.97
30 degrees	9.4E-4	1.75E-5	4.44E-5	0.53	0.72
60 degrees	9.39E-4	2.48E-4	-1.92E-4	0.39	0.64
0 degrees	6.33E-4	1.44E-4	-7.15E-5	0.56	0.94

Table 2 : Coefficients of the Lorenzian function and coefficient of determination for the cases where horizontal louvers were installed.

For vertical fins power functions fitted better the obtained results :

$$CF = A2\ Ar^{-B} \qquad (7)$$

The corresponding parameters A and B as well as the correlation coefficients for the various tilt angles are given in Table 3.

Shading: Vertical louvers	A2	B	Correlation Coefficient
45 degrees east	0.066	0.31	0.81
0 degrees	0.204	0.2	0.84
45 degrees west	0.06	0.3	0.74

Table 3. Coefficients for equation 7.

The obtained CF values have been used to recalculate the air flow for all the experiments. The corresponding correlation coefficients between the predicted and measured values when the CF coefficient is used, are given in Table 4.

Shading	Correlation coefficients
No shading	0.99
Horizontal louvers 30 degrees	0.98
Horizontal louvers 60 degrees	0.97
Horizontal louvers 0 degrees	0.9
Vertical louvers 45 degrees east	0.99
Vertical louvers 0 degrees	0.98
Vertical louvers 45 degrees west	0.96

Table 4. Correlation coefficients between measured and predicted air flow rates when the CF factor is used.

As shown the use of the appropriate CF coefficients considerably improves the accuracy of network models in predicting the air flow rate through large opening equipped with movable shading devices.

The developed algorithms are valid for the specific solar control devices and for the range of climatic parameters under which the experiments have been carried out.

5. References

1. Sciuto S : 'Final Report of the Solar Contro Task', PASCOOL Research program, Commission of the European Commission, Directorate General for Science, Resaerch and Development, 1996.
2. Yakubu and Sharples : 'Airflow through modulated louvre systems', Building Serv. Eng. Res. Technol. 12(4), 151-155, 1991.
3. Matsura M : 'General calculation method of illuminance from verical louver blind system'. Proc. of the International daylighting conference, 1983.
4. Goral et. al. Modelling the interaction of light between diffuse surfaces, Computer Graphics, Vol.18,No 3, 1984.
5. Ward G.: ' RADIANCE Lighting Simulation System ', SIGGRAPH 1994.
6. Kajiya J. :'The rendering equation'. Computer Graphics ,Vol.20, No4, 1986.
7. Wouters P. and Wandaele L. : 'The PASSYS Services'. Final Report of the PASSYS Research project. European Commission, Directorate General for Science, Research and Development, 1995.
8. Perez R. and Kendirck J (eds) : 'Guide to recommended practice of daylight measurements', CIE TC 3-07, 1991.
9. Tregenza P. R. : 'Daylight Coefficients', Lighting Research and Technology, Vol. 15, No 2, 1983.
10. Santamouris M and D.N. Asimakopoulos, (Eds) : 'Passive Cooling of Buildings', James and James Science Publishers, London, 1996.
11. Regard M. : 'Contribution a l' etude des mouvements d'air dans le batiment a l' aide d' un code de champ : Application a la ventilation naturelle d' un local par une ou deux grandes ouvertures'. Ph. Thesis presented to the Institut National des Sciences Appliques de Lyon. 1996.
12. Feustel H., Allard F., Dorer V., Garcia Rodrigez E., Herrlin M., Mingsheng L., Phaff H., Utsumi Y., Yoshibo H. Fundamendals of the multizone air flow model -COMIS, International Energy Agency- Air Infiltration and Ventilation Centre, Technical Note AIVC 29, Coventry, U.K. 1990
13. Santamouris, A. Argiriou, D. Asimakopoulos, N. Klitsikas and A. Dounis : 'Heat and Mass Transfer through Large Openings by Natural Convection. ' Journal Energy and Buildings, 23,p.p. 1-8, 1995.
14. Dascalaki E., F. Allard and Santamouris M. : 'Natural Ventilation Studies in the framework of the PASCOOL Project'. Proc. Int. Symposium Passive Cooling of Buildings, M. Santamouris and D.N. Asimakopoulos, (Editors), Athens, Greece, June 1995.
15. Dascalaki E., M. Santamouris, A. Argiriou, C. Helmis,, D.N. Asimakopoulos, K.Papadopoulos and A. Soilemes : 'Predicting Single Sized Natural Ventilation Rates in Buildings', Solar Energy, 55, p.p. 327-341, 1995.