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Simulación de la transmisión de radiación solar directa en un hueco aire-luz de edificio

Simulation of direct solar radiation transmission in a building well

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Resumen

Con un modelo estocástico se simula la propagación de radiación solar directa en un hueco aire-luz de superficie interior cuasiespecular. Para situaciones típicas fueron calculadas las irradiancias sobre las ventanas internas y también la base del hueco. Los resultados numéricos, desde el punto de vista de la iluminación natural (de edificios), son significativos.

Palabras claves: radiación solar, reflexión, iluminación natural, hueco aire-luz, estocástico, edificio.

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Abstract

Propagation of direct solar radiation in a simple design light-well of quasi-specular inner surface is simulated using a stochastic model. Irradiances on inner windows and also on the well bottom were calculated for typical situations. The numerical results are of significance from the daylighting point of view.

Keywords: solar radiation, reflection, dayligthing, light-wells, stochastic, building.

Introduction:

When designing multi-storey buildings, it is sound practice to place windows facing a common vertical duct as a way of illuminating and ventilating central rooms.

These ordinary air/light wells supply a certain amount of solar radiation through the windows (those placed on the well walls). Wall surfaces are usually rough, and consequently, they generate a rather diffuse reflection of the incoming natural light.

Using light colors, it is possible to transmit radiation in depth; but at the sight of the well interior, the observer behind any inner window is exposed to unpleasant glare effects due to horizontal, or almost horizontal, reflected rays. To avoid this phenomenon one sort of high specular covering must be applied to the well surface. In this way the apparent solar altitude angle will remain almost the same after several inner reflections.

The daylight performance of a simple design light-well, but with a quasi-specular inner surface is here numerically simulated, for typical situations. This modeling field has been little explored up to now.

Similar problems related with the transmission of daylight by means of successive reflections on the inner surface of hollow ducts (or pipes) have received some attention since the eighties [1, 2, 3, 4]. In [5, 6], building light-wells of rather complex design has been experimentally studied.

A review of the scientific literature on the subject shows that in general, the basic purpose is to determine, either the radiation levels, or the photometric conditions at the end of the ducts, as effects of a known solar radiation input.

In the present contribution, instead of a unique outgoing flux (radiant or luminous), two quite different ones are computed: a) the flux which reaches the bottom of the well; and b), the lateral fluxes through the windows placed facing the well interior.

The model was built on the basis of the Snell´s law. Stochasticity is introduced into it by using a Monte Carlo scheme [7]. As outputs of the model, the inner irradiances relative to the outer solar irradiance on a horizontal plane were chosen.

To characterize the single light reflection phenomenon of a one direction incident radiation onto a low roughness reflecting surface, it was assumed that the radiation scattering is given by a narrow Gaussian distribution which is centered around the specular reflection direction.

THE MODEL

Solar radiation flux entering into a light well can be written as

$$\Phi = (\mathbf{I} \cdot \mathbf{k}) \,.\, S \qquad (1)$$

where **I** is the vector defined by the direction, sense and intensity of direct solar radiation, **k** is the z-axe versor (see figure 1) and S is the area of the well cross section.

The radiation incidence area (at the top of the well) is divided into a given number of equal cells, being the incident energy flux on each cell: $N\ \Delta E/\Delta t$, where ΔE is an elemental quantity of radiant energy (or "photon"), Δt an arbitrary lapse time and N, the number of incident photons on the cell in a Δt time (here, "elemental" means that there are not any partition of ΔE in the model.

A vectorial algorithm simulates, step by step, the photons trajectories and photon-escape events through control surfaces (inner windows and the top and bottom of the well).

When a photon is intercepted by a reflecting surface the probability of absorption is evaluated by means of a uniform distribution. In the case of no absorption, specular reflection direction is calculated by the well known vectorial formula:

$$\boldsymbol{\rho}_o = \mathbf{i}_o - 2\ (\mathbf{n} \cdot \mathbf{i}_o)\ \mathbf{n} \qquad (2)$$

Where **n** is the normal at the reflecting surface, $\mathbf{i}_o$ is the versor which defines the sense and direction of the incident photon and $\boldsymbol{\rho}_o$ is the versor corresponding to the reflected photon.

To simulate the quasi-especular reflection phenomena it is used a Gaussian perturbation of the perfect specular reflection direction given by (2) [8].

The absolute energy gain for the i window , in a time Δt is

$$\Delta E_{wi} = \mu_{wi}\ \Delta E$$

μ_{wi} : number of photons passing through i window in a Δt time

In a similar way the absolute energy at the bottom (neglecting any reflection from it) can be expressed as

$$\Delta E_b = \mu_b \cdot \Delta E$$

μ_b : number of photons which reach the bottom in a Δt time.

In order to quantify the radiation energy distribution it is convenient to define:

a) the energy gain of i window as a fraction of the total incident direct radiation: $G_{wi} = \Phi_{wi}/\Phi$, where $\Phi_{wi} = \Delta E_{wi} / \Delta t$

b) the relation between the flux which reaches the well bottom $\Phi_b = \Delta E_b / \Delta t$, and the incident one:

$\tau = \Phi_b / \Phi$ or "well transmittance"

Multiplying G_{wi} by the factor $f = S/S_w$ (S_w : window area), the irradiance on i window is obtained as a fraction of the external irradiation on a horizontal plane , without considering diffuse radiation. This new quantity, $I_{wi} = G_{wi}.f$, supplies relevant information about the daylighting method in study.

Also it is calculated the global fraction of absorbed radiant energy by means of the expression $\alpha = \Phi_a/\Phi$, where Φ_a is the total absorbed flux by the reflecting material.

The energy lost by retroreflection, that is , the radiant flux from the top of the well, is negligible for the cases here shown. So, from the energy conservation law, the following relation holds:

$$\tau + \alpha + \Sigma G_{wi} = 1$$

A reasonable validation of the computational code was obtained by performing a series of numerical experiments regarding energy conservation, convergence and fitting of exact solutions. It can be added that the solar intensity is automatically generated by a well known algorithm that process initial data of time (date, solar hour) and latitude.

Calculations Results

The dimensions and orientation of the light well that were chosen to perform the numerical examples are displayed in fig. 1. There are three stories and four windows in each storey.

It was selected an absortivity value of the reflecting material equal to 0.2. The 3σ value of the normal distribution fit a 10 degree angle of deviation respect of the specular reflection direction. For basic Montecarlo program running it was used a total photons number equal to $3.\ 10^4$.

Diffuse radiation was not taken into account.

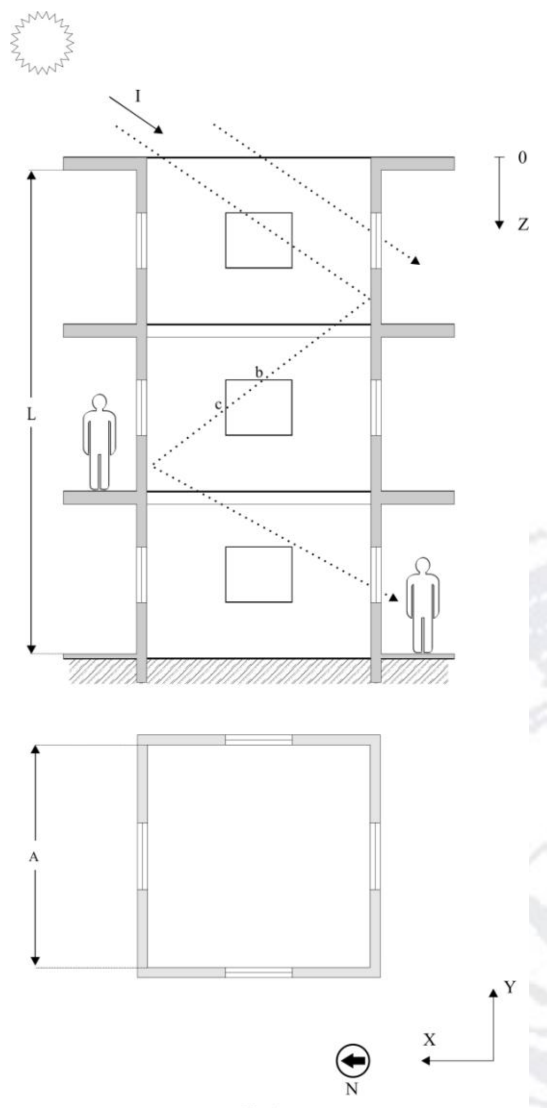

Figure 1: Light well of side A square plant and height L, with four inner windows per level. The common windows dimensions are b x c and b/c = 1.2, A/c = 4 and L/c = 9.

Most of the simulations correspond to local latitude of 33 ^{o} S which, in the country, approximates the main cities latitudes (Table I). Due to the problem symmetry with respect to the North–South direction, all the results are also valid for the North hemisphere.

Additional results, for higher and lower latitudes are presented too (Tables II and III).

Solar time (hour)	0	1	2	3	4
Ground Level	12.7	19.8	15.6	9.8	2.1
First Floor	15.1	30.4	37.7	20.7	10.0
Second Floor	36.6	46.3	62.3	76.4	87.7

Table I: Mean irradiance on windows facing the light-well interior (fig. 1) as a percentage of outer (direct) solar irradiance on the horizontal plane, for the winter solstice.
Calculations were made for a 33 ^{o} latitude and an absortivity of the reflecting material equal to 0.2. Diffuse radiation was not taken into account (0 solar hour corresponds to solar noon).

Solar time (hour)	0	1	2	3	4	5
Ground Level	18.9	16.0	16.1	19.2	11.7	4.3
First Floor	20.4	23.9	22.8	33.1	27.4	17.1
Second Floor	23.1	32.8	43.4	53.9	73.8	102.9

Table II: Hour by hour evolutions of mean irradiance on inner windows as a percentage of the outer irradiance on the horizontal plane (direct component) in a light well located at a latitude of 43^{o} , during the equinoxes.

Solar time (hour)	0	1	2	3	4	5
Ground Level	11.8	12.8	15.1	16.5	15.8	8.1
First Floor	11.2	17.3	19.3	26.8	30.3	24.4
Second Floor	10.0	17.0	27.0	37.2	56.6	85.4

Table III: Hour by hour evolutions of mean irradiance on inner windows as a percentage of outer irradiance on the horizontal plane (direct component) in a light well located at a latitude of 23^{o}, during the equinoxes.

To calculate absolute irradiances, Tables I to III can be used in connection with standard models which determine the atmosphere transmittance for direct solar radiation, as for instance the Hottel one [9]. Using this latter model it was built Fig. 2, where absolute irradiances values are shown. In all cases, 0 solar hour corresponds to solar noon.

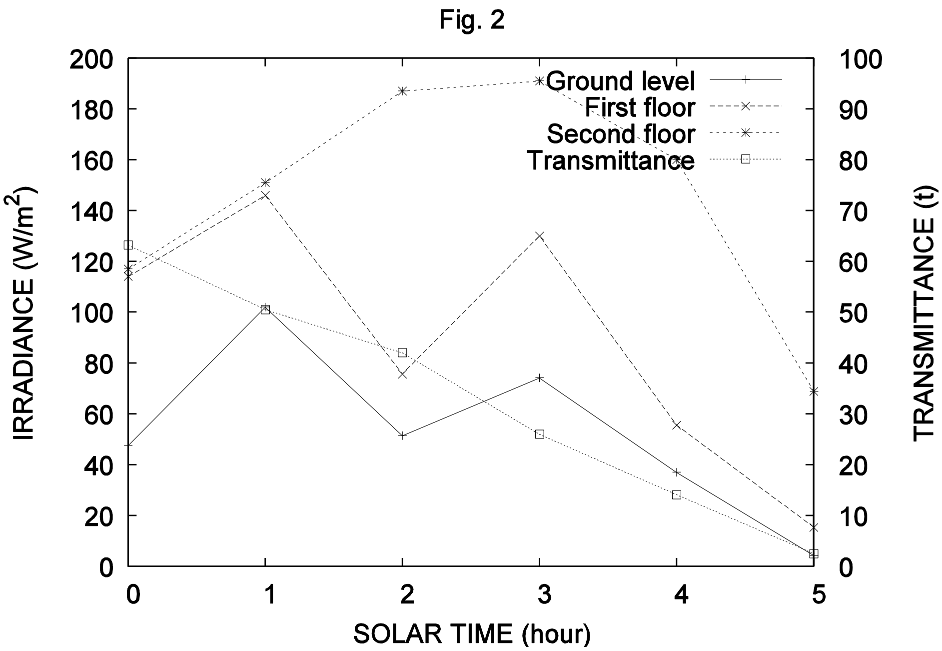

Figure 2: Mean absolute irradiance on inner windows (in W/m2) and total transmittance τ (in percentage) in a light well located at a latitude of 33 gr., during the equinoxes; for a clear day, at sea level. Differences between spring equinox and fall equinox are not considered in this approach.

An inspection of the irradiances curves in Fig. 2 shows that all of them decrease in a monotone way for solar time greater than 3hr. This common trend is due to the great number of inner reflections at low values of the solar altitude angle. But, when considering the complete solar time range, other factors must be taken into account in order to explain the mean irradiance evolution, as the variation of the solar azimuth angle. At solar noon, for instance, the east and west walls of the well are almost not irradiated; the solar irradiation on these walls increases from 0hr to 1hr, and consequently, the mean irradiance also increases.

Conclusions and Perspectives.

At the present research stage the gaussian model seems a suitable approach to treat quasi-specular successive reflections. Experimental bidirectional spectral reflectivity [7] data for specific reflecting surfaces (of practical utility) could be used in the future to improve the calculation code.

Numerical values displayed in tables I to III can be used with any solar direct radiation data to predict the corresponding internal irradiances values.

These irradiances, assuming that the solar spectrum is little modified by the reflections, can be considered as “solar irradiances”, and then be used as inputs to determine illumination distributions into the rooms which are illuminated from the well; provided that all the complementary data are known: geometry, windows glass transmittance (spectral), reflectivities of the room surfaces, optical properties of diffusers (if needed), etc. Undoubtedly this is a complex task, but not so different to the one involved in the dayligthing calculations for a room which is illuminated through a window of the building facade. That is to say, in both situations, primary data of solar radiation can be used to obtain inner illuminances.

It can be expected significant solar radiation levels for either illumination or growing plant (photosynthetical active radiation) purposes.

In particular, to visualize the availability of natural illumination, a luminous efficiency of solar radiation equal to 100 lumen/watt [5] can be assumed.

As an example, it can be calculated the mean illuminances onto the windows at the lowest level , for 43 degree latitude, during the equinoxes. Using this latter efficiency figure in combination with Table II irradiances values and the Hottel model [9], it is found that mean illuminances are over 2200 lux between 4am to 4pm , with a maximum near 11000 lux at solar noon. On the contrary, when the well inner surface is smooth but of a dark color (absortivity around 0.5) , the model predicts that the corresponding illuminances values are much smaller.

It is worth to observe the considerable high values of the solar transmittance. This supports the idea of using the light- well as a sort of atrium, with a garden.

To appreciate the potential of this new passive daylighting strategy the results here discussed are enough; but, it is clear that more numerical-experimental research is required to gain a better insight on the subject.

Regarding the reasons to do additional research efforts, it must be said:

On one hand, the method can be implemented in existing buildings with an air-light well of similar characteristics to the one here studied .This can be done by attaching a reflecting film to the well surface (comments on specific techniques are beyond the scope of the this work).

On the other hand, the development of low cost high reflecting films would permit the method to be applied in deeper wells.

Also that, in any case, a reduction of the electrical energy consumption for diurnal illumination implies more sustainable buildings.

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In memoriam Professor L.C.A. Fernandez.

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