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Modelling of radiation in natural light pipes applied to an agricultural construction

Modelación de la radiación en tubos de luz natural aplicada a una construcción agropecuaria

BETANZOS-CASTILLO, Francisco†*, FUENTES-CASTAÑEDA, Pilar and CORTEZ-SOLIS, Reynaldo

Tecnológico Nacional de México/TES Valle de Bravo, México.

ID 1st Author: *Francisco, Betanzos-Castillo* / **ORC ID:** 0000-0002-7245-703X, **CVU CONAHCYT ID:** 206209

ID 1st Co-author: *Pilar, Fuentes-Castañeda* / **ORC ID:** 0000-0001-6567-9614, **CVU CONAHCYT ID:** 428699

ID 2nd Co-author: *Reynaldo, Cortez-Solis* / **ORC ID:** 0000-0001-7519-1815, **CVU CONAHCYT ID:** 1113392

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Abstract

Light energy in facilities whose environment is not artificially controlled has depended entirely on the hours of light coming from the outside. To counteract this limitation and increase the luminous flux, it was proposed to develop the study and design of a natural lighting system applied to an agricultural construction, using concentrators to capture, concentrate, redirect and introduce the sun's rays into the space to be illuminated and achieve a reduction in the use and cost of conventional energy. But before wasting time and money building the design, the modeling and simulation allows to generate certainty that the radiation model to be implemented, really meets the necessary characteristics, thus was used the CFD simulation technique using Fluent of Ansys Workbench, which generated confidence that the model to be used is the one required for the installation and activities to be performed within the agricultural construction selected.

Luminous flux, Agricultural, Reduction, Modeling, Simulation

Resumen

La energía luminosa en instalaciones cuyo ambiente no se controla artificialmente ha dependido totalmente de las horas de luz provenientes del exterior, para contrarrestar esta limitante y aumentar el flujo luminoso se desarrolló el estudio y diseño de un sistema de iluminación natural aplicado a una construcción agropecuaria, utilizando concentradores para captar, concentrar, redireccionar e introducir los rayos solares hacia el interior del espacio a iluminar y lograr una reducción del uso y costo de energías convencionales. Pero antes de perder tiempo y dinero construyendo el diseño, la modelación y simulación permiten generar certeza de que el modelo de radiación que se pretende implementar realmente cumpla con las características necesarias, de esta manera se utilizó la técnica de simulación CFD empleando Fluent de Ansys Workbench, la cual generó la confianza en que el modelo a utilizar es el requerido para la instalación y las actividades a realizar dentro de la construcción agropecuaria seleccionada.

Flujo luminoso, Agrícola, Reducción, Modelado, Simulación

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*Correspondence to Author (E-mail: fbetanzoscastillo@gmail.com)
† Researcher contributing as first Author.

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Introduction

Most human and biological activities on earth are governed and powered by the sun, as the sun has been a source of illumination throughout human history. The development and use of efficient artificial lights has led humans to separate themselves from the healthiest and best source of illumination: natural light. Studies have shown the benefits in health, safety and labor productivity when buildings are naturally illuminated (Boyce, 2022; Roche, 2000).

In addition to the quality of natural light, another reason to use it is its compatibility with lighting control systems to achieve a reduction in the use and cost of conventional energy, thus achieving a sustainable system.

Undoubtedly, sunlight is beneficial inside facilities that house living beings (air quality, non-toxic materials and occupant health) (Gissen, 2002), but the use of artificial light during daylight hours is paradoxical, since there is an abundance of natural light for illumination (Muhs, 2000). Consequently, although artificial light provides sufficient levels of illumination, it cannot provide physiological and psychological comfort (Brainard & Glickman, 2003) (Jenkins & Munner, 2003:2004), benefits of natural light. However, transporting natural light into the facility is sometimes not possible with simple windows and/or domes. Solar concentrators coupled with light pipes are passive systems, and represent a simple solution to the problem of natural light deficiency.

Among the biological activities that living beings perform throughout their lives, those that occupy most of it, not only in time but also in space, are work, production, rest, among others. In this sense, these activities, in order to be developed in an effective way, require that light (environmental characteristic) and vision (personal characteristic) complement each other, since it is considered that 50% of the sensory information received by animals is visual, that is, it has light as its primary origin, and in the case of plants it is required to carry out the photosynthesis process. The integration of these aspects will result in greater productivity, comfort and safety in an efficient and effective manner.

The light intensity experienced by animals housed close to the source can differ markedly from that experienced by others farther away, because intensity is inversely proportional to the square of the distance from the light source. There are few studies on the effect of light quality or light spectrum on animals. It has been found that the lighting in rooms where animals are housed should as far as possible have the characteristics of sunlight.

Photoperiod is probably the characteristic of light that influences animals the most. It influences the circadian rhythms found in biochemical, physiological, and behavioral aspects in animal models stimulated and synchronized through the neuroendocrine pathway. The circadian cycle may affect the animal's response to drugs or its resistance to inoculated infectious organisms (Mcsheehy, 1983). The light/dark relationship may affect reproductive performance and sexual maturity. It is believed that, if a change occurs in an animal's photoperiod, experiments should not be performed on it for at least one week (Davis, 1978). If the light period is interrupted by darkness, there are few important effects; conversely, if the reverse occurs, endogenous rhythms may be significantly affected. In Table 1, the illuminance conditions required for each type of species are presented.

Species	Illuminance [Lx]
Bovine cattle	215 - 538
Rams	538
Hogs	500-1000
Horses	200-800
Poultry	10-35

Table 1 Specific environmental lighting considerations
Source: Canadian Council for Animal Welfare (CCPA)

Computational Fluid Dynamics (CFD) has great potential for predicting the control of air flows, temperature distribution and radiation, which are essential to ensure optimal production conditions and healthy working environments in animal buildings, but successful use of the technique requires knowledge of suitable methods for handling boundary conditions and mesh distributions in computational space (Bjerg, 2002). Computational fluid dynamics is based on the equations governing fluid dynamics (continuity, momentum and energy).

These equations are mathematical expressions of the three physical principles governing fluid dynamics:

- Conservation of mass
- Newton's second law
- Conservation of energy

Its derivation is typically explained by a mass and energy balance over a control volume, Equation 1 being a generalized way of expressing it (Anderson, 1995).

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla.(\partial\pi\phi) = \nabla.(\Gamma\nabla\phi) + S\phi \quad (1)$$

Methodology

Mathematical Model

The (DO) model solves the radiative transfer equation (RTE) for incident solar radiation at a finite number of discrete solid angles, each associated with a fixed direction vector $\vec{s}$ in a Cartesian coordinate system (x, y, z). DO model solves the radiation direction vector transport equations $\vec{s}$, [-], and the position vector $\vec{r}$ [-], (Raithby and Chui, 1990; Chui y Raithby, 1993). The RTE for spectral intensity $I_\lambda(\vec{r}, \vec{s})$ is:

$$\nabla \cdot (I_\lambda(\vec{r}, \vec{s})\vec{s}) + (\alpha_\lambda + \sigma_s)I_\lambda(\vec{r}, \vec{s}) = \alpha_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r}, \vec{s}')\Phi(\vec{s} \cdot \vec{s}')\, d\Omega' \quad (2)$$

Where: I_λ is the intensity of the radiation of wavelength λ, Wm^{-2} sr^{-1}, λ is the wavelength, m^{-1}, $\vec{s}'$ is the direction vector of dispersion, [-], α_λ is the spectral absorption coefficient, 1/m, Ω' is the solid angle, [°], and $I_{b\lambda}$ is the intensity for a black body given by the Plank function, Wm^{-2}. The dispersion coefficients σ_s, 1/m, Φ the spectral phase function, [-] and the index of refraction n of a medium b [-], are assumed to be wavelength independent. The phase function Φ is considered to be isotropic, the angular space4π for any spatial location is discretized in $N_\theta \times N_\varphi$ for solid angles ω_i, called control angles θ and φ are the polar and azimuthal angles, measured with respect to the global Cartesian system. (x, y, z). The RTE equation is integrated over each wavelength. Then the intensity $I(\vec{r}, \vec{s})$ for each $\vec{s}$ and $\vec{r}$, is calculated by using:

$$I(\vec{r}, \vec{s}) = \sum_k I_{\lambda_k}(\vec{r}, \vec{s})\Delta\lambda_k \quad (3)$$

The RTE equation is coupled with the energy equation through the radiation source term s_h over a control volume given by equation:

$$s_h = -\frac{\partial q_{ri}}{\partial x_i} = \alpha_\lambda\left(4\pi I_{b\lambda}(\vec{r}) - \int_{4\pi} I(\vec{r}, \vec{s})\, d\Omega\right) \quad (4)$$

Where x_i component in the i-direction, m, α_λ is the coefficient of spectral absorption, calculated from absorptivity α, with the following ratio, according to optical thickness d, [m]:

$$\alpha_\lambda = \frac{1}{d}\ln\left(\frac{1}{1-\alpha}\right) \quad (4)$$

Experimental configuration

To demonstrate the performance of the light pipes, experimentation is essential as shown in figure 1. From the known pipe dimensions (i.e. length, L and diameter, d) and from the data collected for a set of light tubes of 600 mm length and diameter equal to 330 mm. As a result of these data, an approximate relationship was obtained between the shape ratio A, $(A = L/d)$ and the light transmitted by the tube. An average ratio of light transmission, τ, obtained from the data, the exterior illuminance, E, and an exponential coefficient of 0.11 per unit of A y the radius of the light pipe cross-section, are used in the luminous flux model, ϕ.

$$\phi = \tau E_{ex}\, e^{-0{,}11A}\, \pi\, r^2 \quad (5)$$

Figure 1 Experimental setup, instrumentation, light tube, luxmeters
Source: Own elaboration

Configuration of the numerical simulation

A cylindrical geometry was implemented for a light pipe with a form ratio of, (A), between the length (L) and diameter (d), $A = L/d = 1.84$, The analysis zones and boundary conditions are shown in Table 2, for the material see Table 3.

The convergence criteria were 10^{-3} for the momentum and continuity equations, while the energy and radiation equations were of 10^{-6}, ambient temperature of 298.35 K of June, an atmospheric pressure of 77046.6798 Pa, a Prandtl number equal to 0.71, Rayleigh number is 5e5, this implies laminar flow.

Zones	Boundary conditions
Indoor and Outdoor Tube Light	Wall
Tube inlet Tube outlet	Velocity inlet Pressure Outlet
Computer proficiency	Wall, Interior, Symetry

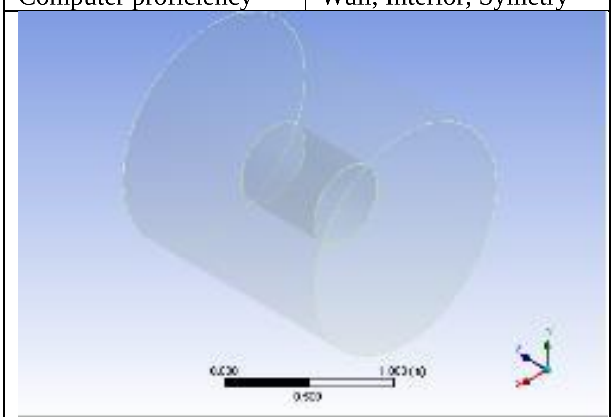

Table 2 CFD model, analysis zones and boundary conditions
Source: Own elaboration

Thermals			
Material	**Pipe**	**Soil**	**Air**
Density, ρ $[kg/m3]$	2700	1300	1.225
Coefficient for conduction, k $[W/mK]$	210	1	0.0242
Specific heat capacity, Cp $[J/kgK]$	909	800	1006.43
Optics			
	Pipe	**Soil**	**Air**
Absorptivity, α	0.1	0.9	0.19
Coefficient of dispersion, α_s	0	-10	0
Index of refraction, n	0.99	1.92	1
Emissivity	0.37	0.95	0.9

Table 3 Optical and thermal properties of the materials. *Source: Own elaboration*

For agricultural construction

Firstly, a construction for rabbit breeding was selected, the development of the 3D CFD simulation using the Rosseland model for radiation on the agricultural construction, and the following were considered:

Environmental characteristics: sun position, Weather calculation, Equation of Time, Longitude Correction, Solar Angles, Declination Angle, δ, the solar declination angle during any given day is considered constant for engineering calculations (Kreith and Kreider, 1978); (Duffie and Beckman, 1991).

Table 4 shows the recommended days for this type of radiation.

Month	Number of the day	Average day of the month		
		Date	N	δ $[grados]$
January	i	17	17	-20.92
February	31+i	16	47	-12.95
March	59+i	16	75	-2.42
April	90+i	15	105	9.41
May	120+i	15	135	18.79
June	151+i	11	162	23.09
July	181+i	17	198	21.18
August	212+i	16	228	13.45
September	243+i	15	258	2.22
October	273+i	15	288	-9.60
November	304+i	14	318	-18.91
December	334+i	10	344	-23.05

Table 4 Day number and recommended average for each day of the month.

The continuity equations equation 6, momentum equation 7 and energy equation 8, requested for the simulation, are presented:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (6)$$

For $\phi = u_i$

$$\rho \frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \rho g_i \quad (7)$$

For $\phi = h \quad (enthalpy)$

$$\rho \frac{\partial}{\partial x_j}(u_i h) = \frac{\partial}{\partial x_i}\left(K \frac{\partial T}{\partial x_i}\right) + \frac{\partial P}{\partial T} + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_i} \quad (8)$$

And considering the values for the Rosseland radiation model:

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Parameter	Specification
Optical thickness aL	For optical thicknesses >3 the Rosseland model is cheaper and more efficient, computationally speaking.
Dispersion and emissivity	The Rosseland model uses a wall temperature slip condition, it is insensitive to the emissivity of the wall.

Table 5 Values for Rosseland radiation model

Finally, we consider the radiation transfer equation (RTE), Eq. 9, for a medium that absorbs, emits and scatters with position $\vec{r}$ in the direction $\vec{s}$ is:

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a+\sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma_s T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}^t)\Phi(\vec{s}.\vec{s}^t)d\Omega^t \quad (9)$$

Results

Experimental

To obtain a mathematical model to predict the behavior of the luminous flux, it is necessary to know the dimensions and optical properties of the light pipe, as well as the shape ratios (length/diameter), which determine the natural light transmittance. To determine the light transmittance, data collection was performed using natural light sensors at the entrance (in sensor) and at the exit (out sensor) of the light pipe. The data record of the natural illuminance variable can be observed in Figure 2, for a given time of the day.

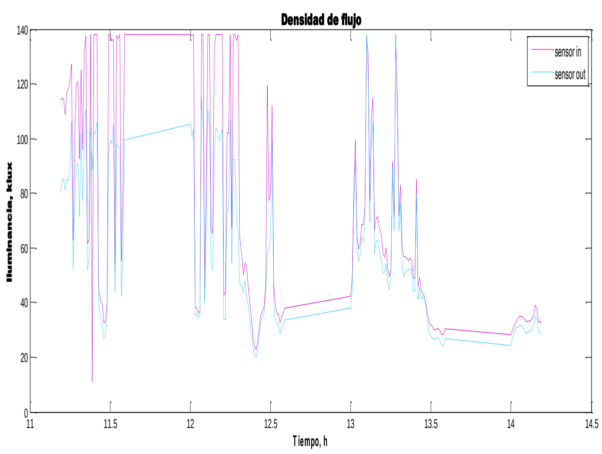

Figure 2 Data collected on luminous flux density
Source: Own elaboration

Numerical simulation

The flow of visible light distribution on and inside the light pipe was simulated with the finite volume method, calculating the effects of solar irradiance for a given time of day, date and geographical position. The calculation of irradiance is given by equations 1, 2, 3 and 4. Figure 3 shows the irradiance contours on the surface of the computational model proposed for the numerical solution.

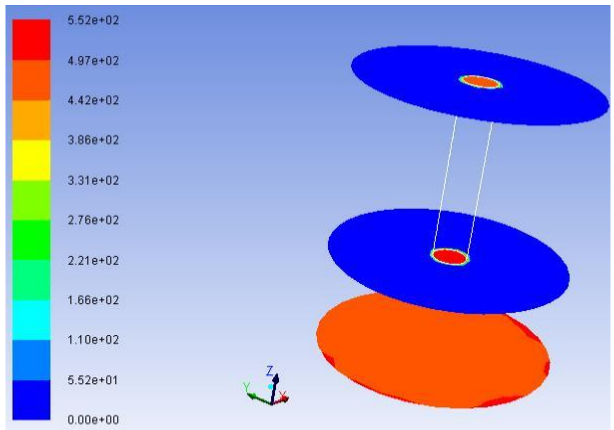

Figure 3 Incident radiation contours on the surfaces of the computational model, units in W/m^2
Source: Own elaboration

Geometry of the model

In order to verify and validate the radiation models of the fluent software, a typical geometry of an agricultural construction for rabbit breeding is generated from its physical characteristics, dimensions and the location of each component (windows, rabbits, etc.), the dimensions are presented in table 6.

Dimensions	Unit, m
Width	4
Height	3.6
Length	24
Cage height	0.35
Cage length	22
Cage width	2

Table 6 General dimensions of the livestock construction for rabbits
Source: Own elaboration

The creation of the construction geometry was carried out in the Ansys workbench program, fluent® 14. The geometry consists of the generation of sketches, plans, 3D operations such as extrude, enclosure, mentioning some operations.

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One of the characteristics of the model design in fluent is the simplification of the problem, that is to say, to simplify the real model according to the purpose of the project. Boundary conditions and types, in figure 4 the computational model is shown, while in table 7, the working conditions are presented.

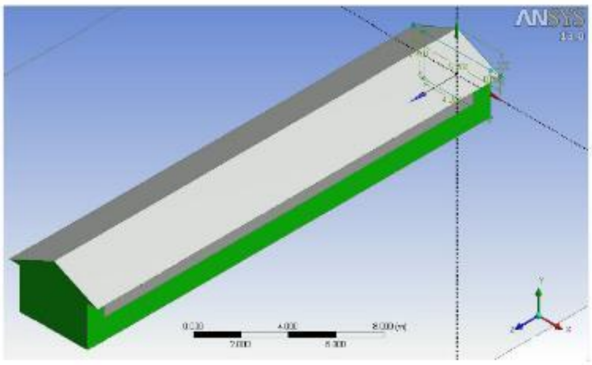

Figure 4 Computational model
Source: Own elaboration

Zones	Boundary conditions
(Farm) roof, walls and floors	Wall
Windows	Porous jump
Rabbits	Wall
Computer proficiency	Symetry, wall, velocity inlet, pressure outlet

Table 7 Boundary conditions
Source: Own elaboration

Simulation in fluent

A temperature of 311.65 K for the living being, an ambient temperature of 298.35 K for the month of June, an atmospheric pressure of 77046.6798 Pa were considered for the computational model of the agricultural construction. Gravity acts downward. A dynamic flow develops due to thermally induced density gradients.

In Figure 5 we can see the behavior of the ventilation inside the building, presenting a minimum velocity of 0.00015 m/s and a maximum velocity of 5.44 m/s.

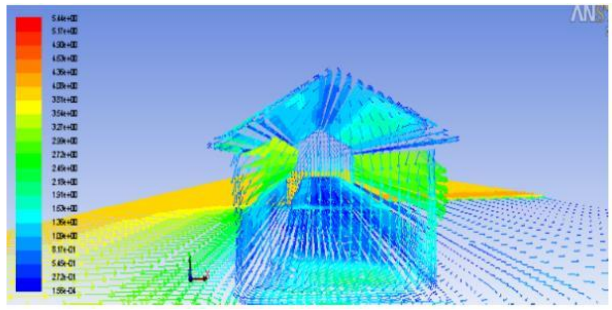

Figure 5 Behavior of lighting vectors in the building
Source: Own elaboration

Discussion

The distribution of the visible light flux on and inside the light pipe was determined numerically and experimentally, the light pipes are effective devices for light transmission in the proposed configuration. As a result of this experience, it is possible to estimate the number and size of light tubes for natural lighting of agricultural constructions, in addition, it will allow important decisions to be taken to satisfy the lighting comfort conditions for the living beings that inhabit and interact in the construction, such as: quantity and quality of transmitted and reflected light, important parameters for the development of plants and animals in controlled environments.

The luminous flux model describes the total amount of light emitted over a given area (tube output), with this it is possible to approximate the watts used in electrical devices of similar use, which could be replaced by light tubes of different dimensions.

The results of the present study could be used in agricultural engineering to understand the interaction of agricultural activity with the levels of natural lighting inside the constructions in such a way that it could be used to improve their bioclimatization. Thus, by making the decision to install light tubes inside these spaces, energy costs can be reduced and energy consumption can be significantly reduced.

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Conclusions

The flow of visible light distribution on and inside the building was simulated with the finite volume method, calculating the effects of solar irradiation for a given time of day, date and position, which will allow us to make important decisions to be taken to meet the lighting comfort conditions for living beings that inhabit and interact in the building, such as: quantity and quality of transmitted and reflected light, important parameters for the case of plants and animals.

The agricultural constructions of specialized production need a continuous control of the interior climate, and knowing the distribution of light in the visible zone is of great relevance for the agronomic benefits that this represents. The results of the present study could be used in agricultural engineering to understand the interaction of agricultural activity with the levels of natural lighting inside the buildings in such a way that it could be used to improve their bioclimatization.

References

Anderson, J. D. and Wendt, J. Computational fluid dynamics. Vol. 206. New York: McGraw-Hill, 1995.

Bjerg, B., Svidt, K., Zhang, G., Morsing, S., & Johnsen, J. O. (2002). Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. Computers and Electronics in Agriculture, (2002) vol.34 (1-3), 223-235.

Boyce, P. (2022). Light, lighting and human health. Lighting Research & Technology, 54(2), 101–144. https://doi.org/10.1177/14771535211010267

Brainard, G., & Glickman, G. (2003). The biological potency of light in humans: Significance to health and behaviour. Proceedings of 25th Session of the CIE, 1, págs. I.22-I.23. San Diego, USA.

Davis, D. E. (1978). Social behavoir in a laboratory environment. National Academy of Sciences, 44-64.

Duffie, John A. Beckman, William A. (1991). Solar Engineering of Thermal Processes. Wiley. ISBN 0471510564, 9780471510567

E. H. Chui & G. D. Raithby (1993) Computation of radiant heat transfer on a nonorthogonal mesh using the finite-volume method, Numerical Heat Transfer, Part B: Fundamentals, 23:3, 269-288, DOI: 10.1080/10407799308914901

Gissen, D. (2002). Big & green: toward sustainable architecture in the 21 st century. Princeton Architectural Press.

Jenkins, D., & Munner, T. (2003:2004). Modelling light-pipe performances a natural daylighting solutions. Building and Environment, 38, 965-972. DOI: 10.1016/S0360-1323(03)00061-1

Kreith, A., & Kreider, F. (1978). Principles of solar engineering. New York: McGraw-Hill.

Mcsheehy, T. (1983). The overview of the state-of-the-art in environmental monitoring. Academic Press, 161-182.

Muhs, J. D., 2000. Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems, Proceedings of ASES 2000 Conference, Wisconsin, June 16-21.

Raithby, G D, & Chui, E H. (1990) A finite-volume method for predicting a radiant heat transfer in enclosures with participating media. United States. https://doi.org/10.1115/1.2910394

Roche L., D. E. (2000). Little fair PJ. Occupant reactions to daylight in offices. Lighting Research and Technology, 32(1), 19-26. DOI: 10.1177/096032710003200303