COMPUTATIONAL SIMULATIONS FOR PREDICTING VERTICAL DAYLIGHT LEVELS IN ATRIUM BUILDINGS

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ABSTRACT

This paper investigates the impact of well geometry and surface reflectance on vertical daylight levels in atria with square forms under a CIE standard overcast sky. By reviewing some previous investigations and comparing with scale model measurements the vertical daylight factor calculated using Radiance are validated. More simulated vertical daylight factors for a very wide range of atrium geometries and reflectances are given. From the results the attenuation and distribution of the vertical daylight levels on the wall of a square atrium with different reflectances are displayed. Also, the comparisons between simulations and two analytical theories have been performed. Finally some conclusions for supporting daylight design in atria are presented.

KEYWORDS

Atrium, Vertical daylight level, Radiance simulation, Validation, Theoretical analysis

INTRODUCTION

The atrium has become a significant architectural form over the past 30 years in that it can help resolve many environmental issues. This is particularly true in deep plan commercial and office buildings (Hung and Chow, 2001). Architects and engineers have often used atria as a sustainable design strategy to achieve benefits such as passive heating and cooling, ventilation and daylighting. Daylight use in an atrium is particularly beneficial as the atrium well can allow natural light to reach potentially dark core areas and decrease energy consumption by reducing artificial lighting use.

Much of the research investigating daylight in atria has tended to focus upon illuminance levels on horizontal surfaces such as the atrium well floor and working planes. However, vertical surface daylight levels in atria are probably more important in terms of indicating the feasibility of spaces adjoining the atrium well being adequately daylit (Aizlewood, 1995). Only a few measurements and theoretical analysises about this issue have been presented (Oretskin, 1982; Aizlewood, 1995; Boubekri, 1995; Littlefair, 2002; Sharples and Lash, 2004) and the results achieved are limited. It is still essential to carry out more investigations in order to get more detailed information which could effectively support the preliminary design practice.

Two key parameters influencing vertical daylight levels in atria are the well geometry and surface reflectance (Sharples and Lash, 2007). In this study, the whole analysis was focused on investigating the impact of well geometry and surface reflectance (including the wall reflectance and the floor reflectance) on vertical daylight levels. The distribution of vertical daylight level across the atrium well walls was also investigated to identify the most suitable positions for adjoining daylit spaces off the atrium well (i.e. the area with higher vertical daylight levels).

Radiance, a ray-tracing package, was used to predict daylight levels on the vertical surfaces of atria under a CIE standard overcast sky. A validation analysis about Radiance simulation was firstly presented. After this, simulations of vertical daylight levels in atria with various well geometries and surface reflectances were performed. Finally the comparisons between the Radiance simulations and analytical expressions for vertical daylight level were made.

VALIDATION ANALYSIS

Radiance application and validation review

Radiance has already been validated by several studies over ten years ago (Mardaljevic, 1995; Fontoynont et al., 1999; Roy, 2000). These investigations showed Radiance simulations could achieve a relatively high accuracy in typical daylit spaces compared with model measurements and theoretical analysis. Today it has become the most powerful package for simulating complex scenes and supplying more precise results. A recent study (Laouadi et al., 2008) even used Radiance as a benchmark model to validate a general methodology to compute DC (Daylight Coefficient) sets for rooms employing multiple dissimilar components.

For atrium daylighting, Radiance is an indispensable tool in that it could carry out investigation more efficiently than other methods. In one paper (Calcagni and Paroncini, 2004), which investigated the main characteristics of the atrium and their influences on the daylight conditions in the adjoining space and on the atrium floor, most of the results achieved were based on the Radiance simulations. Another recent study (Samant and Yang, 2007) focued on Radiance simulation and the influence of geometry and surface reflectance distribution on daylight factors at the base of atrium. A very important study concerning Radiance validation was carried out in atrium spaces by Aizlewood et al., (1997). It has been found that in atria with a simple square plan and open roof Radiance simulations agreed well with measurements, but slightly underestimated light levels for deeper atria and high reflectance surface. Later, the results were quoted in a IEA report (Fontoynont et al., 1999), which demonstrated the validation analysis of five packages for lighting simulation. The discussion about Radiance applications in it showed that ambient parameters settings are quite crucial for the accuracy of simulated data; improper ambient parameters could bring big errors and convergence testing is essential for each different model.

Comparison of measurement and simulation

In order to further analysize and validate Radiance applications for the vertical surfaces of atria, a comparative analysis between measurement and simulation was obtained. The whole measurement process was described in a journal paper by Sharples and Lash (2004), whose aims were to study the distribution of the relectances of vertical surface and its influence on vertical daylight levels along a central vertical line on square atrium walls (WI = 1). In this study, six scale atrium models with different surfaces were reproduced in a CAD package and input into Radiance to calculate the vertical daylight factors on atria walls under a CIE standard ovestsky. The surfaces of the six models comprised of two different bands: white with reflectance 0.85 and black with refletance 0.02 (see Table 1). There were five positions to be studied along the centre line of atrium wall: 10%, 30%, 50%, 70% and 90% of atrium height (h).

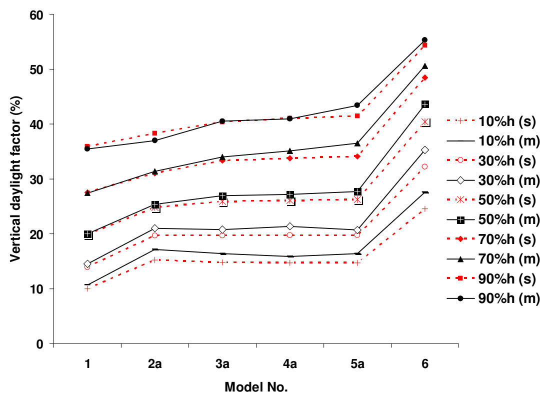

Figure 1: Comparison of vertical daylight factor between measurement (m) and simulation (s).

Figure 1 illustrates the comparison between the measured data and the simulated data for the vertical daylight factor (DF_v) along the centre line of atrium walls. For the relative difference of vertical daylight factor between simulation and measurement, the maximum, minimum and mean values are 11.5%, 0.3%, and 5% respectively (taking the measured data as the reference). The absolute difference between them is less than 5%. This enhances the validation of the simulation for vertical daylight levels in atria.

For the model 1 with black surfaces (reflectance 0.02), the data of two groups agree very well, whilst the simulations of model 6 with white walls (reflectance 0.85) slightly underestimates the measurements. The biggest variations occur on the 10%h, while the 90%h sees the smallest variation. These findings correspond with some previous conclusions about Radiance validation (Fontoynont et al., 1999; Littlefair, 2002). Also, the difference between them could be explained by photometric deviations or inexact geometric correspondence.

This section has demonstrated that Radiance simulation could be a reliable method to carry out calculation of the daylight factor on the atrium walls, although there are some small discrepancies.

DAYLIGHT LEVELS ON THE WALL

In this section Radiance simulations were used to analyse the impact of well geometry and surface reflectance on vertical daylight levels under a CIE standard overcast sky. Well geometry can be quantified in terms of the well index (WI), which is a function of well length, width and height, and well-indexed depth (WID), which, in addition, considers the distance from the top edge of the atrium well (Aizlewood, 1995) – see Figure 2:

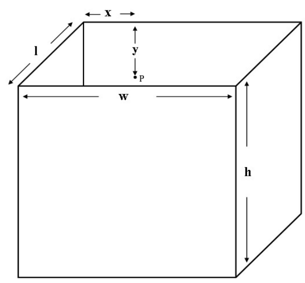

Figure 2: WI and WID definitions.

$$WI = \frac{h(w+l)}{2wl} \quad (1);$$

$$WID = \frac{y(w+l)}{2wl} \quad \text{(rectangular atrium)} \quad (2);$$

$$WID = \frac{y}{w} \quad \text{(square atrium)} \quad (3).$$

The computer models studied were square in plan and were used with a broad array of well index (WI) and well indexed depth (WID) geometries (WI range 0.25 to 1.5 and WID range 0.25 to 1.25 – see Table 2). The atrium models had no roofs. The reflectance of the model surfaces used in the simulations ranged from 0% (perfectly black) to 80% (white), which is a common colour range for building daylighting analysis. In the analysis, the high position, middle position and low position have a height ¾, ½, ¼ of atrium height respectively. The analysized points on the walls were positioned on three vertical lines with horizontal distances from the corner edge of 50%, 30%, 10% of the atrium width respectively. So, the vertical lines were named as: centre line, 30% line and 10% line, which were used in the following analysis. In terms of the surface reflectance, the whole simulations included three parts: atrium models with various uniform reflectances; atrium models with various wall reflectances and a fixed floor reflectance; atrium models with various floor reflectances and a fixed wall reflectance.

Uniform surface

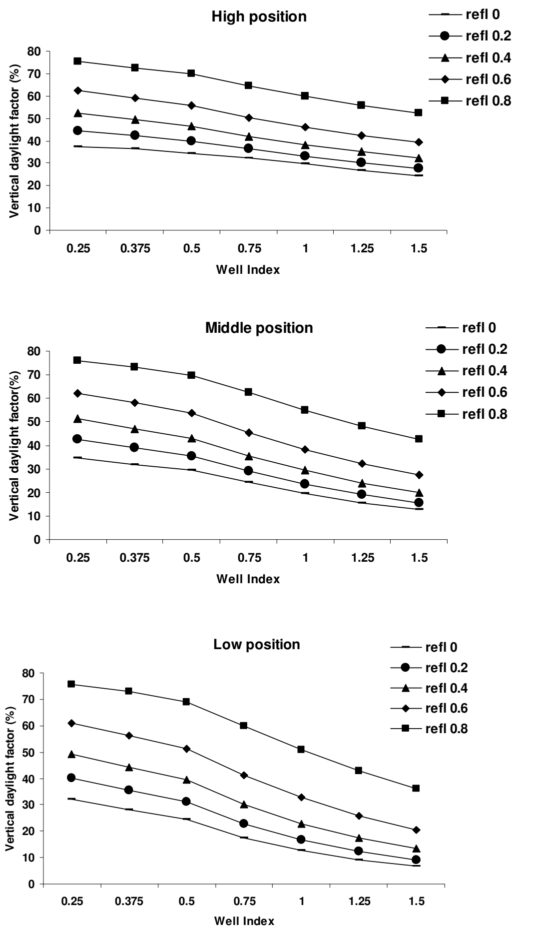

Figure 3: Simulated vertical daylight factor at the centre line of atrium wall.

In this section the atrium models used in the simulations have various uniform reflectances (wall and floor) including 0, 0.2, 0.4, 0.6, 0.8, which are typical values of building surfaces.

Figure 3 illustrates simulated daylight factors at the different heights in the centre line of atrium walls. From the plots, it can be seen that generally the vertical daylight factor decreases with the increase of WI from the shallower models to the deeper models with five different reflectances. Although the WI 0.25 has similar values on three positions, the daylight levels of low positions drop dramatically when WI approaches 1.5. So, the curves of the low position are much steeper than other locations. The comparatively flat curves at the high positions could be explained by the fact that higher parts on the wall receive more sky light than lower parts.With the increase of surface reflectance, the vertical daylight levels become bigger, as would be expected. Nevertheless, daylight levels do not increase in a linear, step-wise fashion as the reflectance is incrementally increased from 0% to 80%. The interval between two adjoining curves increases with the increasing reflectance. The discrepancies between the curve (reference 0) and other four curves are the IRC_v (vertical internal reflected component). Where the position is lower, the IRC_v is bigger. Then, it shows that the lower positions receive more reflected light from the surrounding surfaces.

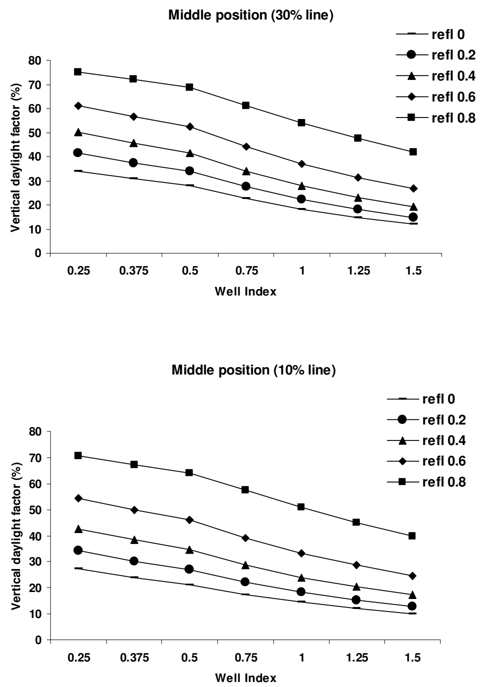

Figure 4: Simulated vertical daylight factor at the 30% and 10% line of atrium wall.

Figure 4 shows simulated daylight factors at middle position in the 30% line and 10% line of atrium walls respectively (the finished curves of high position and low position have not been included in this paper). The same forms and trend as the centre line also occur in the results for 30% line and 10% line.

The largest model (MODEL 7, WI 1.5) was used as a reference case to express the daylight levels across the whole wall. In this analysis, the WID was a function of vertical daylight factor. Figure 5 indicates the simulated vertical daylight factors along the centre line on the wall in MODEL7 with different uniform reflectances. The simulated data vary as an exponential function of WID (well indexed depth), which corresponds to the conclusions from several previous studies (Aizlewood, 1995; Tregenza, 1997). Several regression functions can be derived by curve fitting analysis:

$$DFv = 42.6e^{-0.3WID} \times 100\% \ (R^2 = 0.98 \text{ refl } 0) \quad (4);$$

$$DFv = 44e^{-0.26WID} \times 100\% \ (R^2 = 0.98 \text{ refl } 0.2) \quad (5);$$

$$DFv = 46.7e^{-0.2WID} \times 100\% \ (R^2 = 0.98 \text{ refl } 0.4) \quad (6);$$

$$DFv = 51.3e^{-0.15WID} \times 100\% \ (R^2 = 0.97 \text{ refl } 0.6) \quad (7);$$

$$DFv = 60.7e^{-0.09WID} \times 100\% \ (R^2 = 0.97 \text{ refl } 0.8) \quad (8).$$

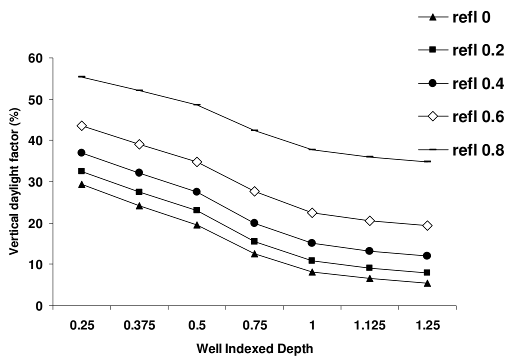

Figure 5: Vertical daylight factor at the centre line of atrium wall (WI 1.5).

Figure 6 demonstrates the distributions of vertical daylight factors along the horizontal lines from centre area (centre line) to corner area (10% line). Three groups of data were selected to represent daylight levels of typical areas on the atrium wall (WI 1.5) including the high part (WID = 0.375), middle part (WID = 0.75) and low part (WID = 1.125). Also, one medium surface reflectance (0.4) was used in this analysis. As expected, for each horizontal area the highest vertical daylght level occurs on the centre line and decreases towards the corner, especially at the higher position of the wall. There is a bigger deviation between the centre line and 10% line at high position than that at the low position, where the dominating component is reflected light. Taking the values of the centre line as a reference (100%), the relative vertical daylight factors (average of three pisitions) for the 30% line and 10% line are 96% and 85% respectively. This displays the area around the 30% line is still the important daylit area.

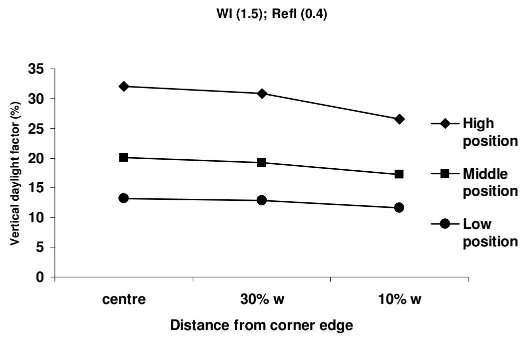

Figure 6: Vertical daylight factor distributions along the horizontal line (WI 1.5).

Wall reflectance

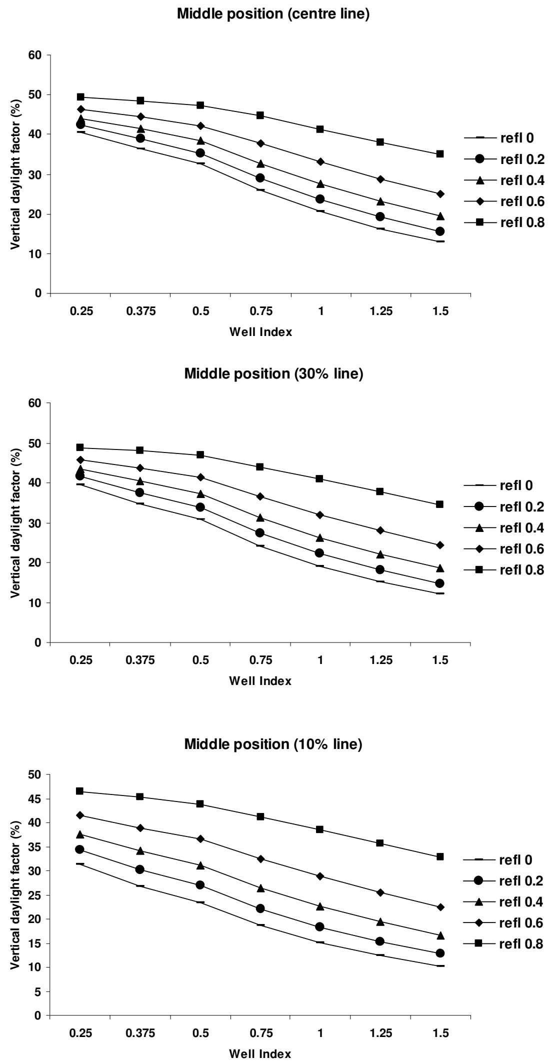

Figure 7: Simulated vertical daylight factor at the middle position of atrium wall.

In this section the atrium models used in the simulations have various wall reflectances (0, 0.2, 0.4, 0.6, 0.8) and a fixed floor reflectance 0.2. The aim of this part is to analyse the impact of well geometry and wall reflectance on vertical daylight levels of atria.

Figure 7 displays the curves of simulated daylight factors at the middle position in the centre, 30% and 10% line of atrium walls. Similar to the curves of uniform surface, the curves with different wall reflectances go down with the increase of WI. Although the centre line and 30% line have similar daylight factors, the values of the 10% line drop dramatically. It would be expected that with the increase of wall reflectance the vertical daylight levels should become bigger. As the reflectance is incrementally increased from 0% to 80%, the interval between two adjoining curves increases. The largest discrepancies occur between the reflectance 0.8 and the reflectance 0.6. Additionally, the discrepancies between different curves interestingly become bigger when the WI tends to larger. This trend is especially distinct in the centre area (around centre line and 30% line).

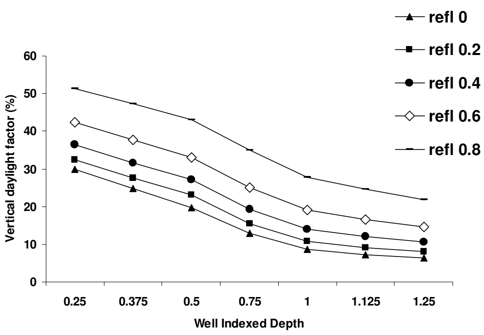

Figure 8: Vertical daylight factor at the centre line of atrium wall (WI 1.5).

For MODEL 7 (WI 1.5) with different wall reflectances, the simulated vertical daylight factors along the centre line on the wall are displayed in Figure 8. Similarly, the simulated data vary as an exponential function of WID and several regression functions can be derived by curve fitting analysis:

$$DFv = 41.3e^{-0.28WID} \times 100\% \; (R^2 = 0.98 \text{ refl } 0) \quad (9)$$

$$DFv = 48.2e^{-0.2WID} \times 100\% \; (R^2 = 0.98 \text{ refl } 0.4) \quad (10)$$

$$DFv = 54e^{-0.19WID} \times 100\% \; (R^2 = 0.98 \text{ refl } 0.6) \quad (11)$$

$$DFv = 63.3e^{-0.15WID} \times 100\% \; (R^2 = 0.98 \text{ refl } 0.8) \quad (12).$$

The function of reflectance 0.2 is the same as (5). The variations among the curves tend to be smaller when WID > 1, which displays the increasing rates of values at high and middle positions are greater than the low position on the wall.

Floor reflectance

In this section the atrium models used in simulations have various floor reflectances (0, 0.2, 0.4, 0.6, 0.8) and a fixed wall reflectance 0.4. The aim of this part is to analyse the impact of well geometry and floor reflectance on vertical daylight levels of atria.

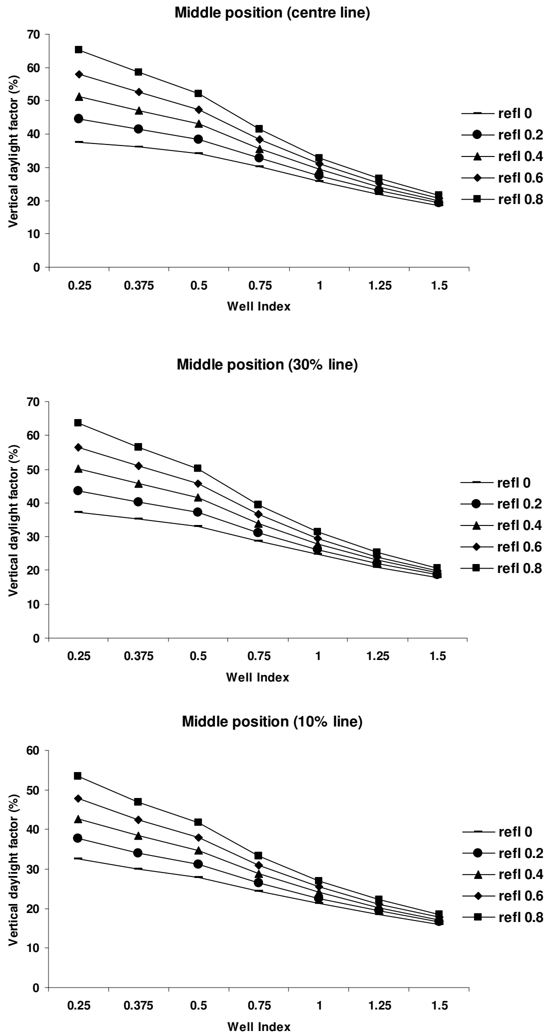

Figure 9: Simulated vertical daylight factor at the middle position of atrium wall.

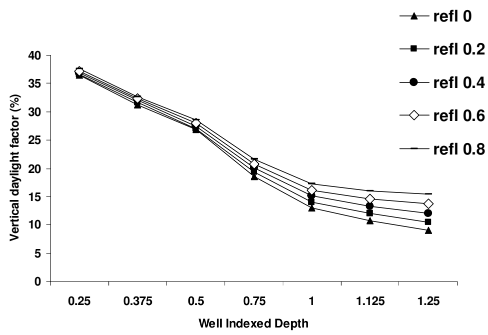

Figure 10: Vertical daylight factor at the centre line of atrium wall (WI 1.5).

Figure 9 shows the curves of simulated daylight factors at the middle position in the centre, 30% and 10% line of atrium walls. The general trends of curves are as follows: vertical daylight factors decrease with the increase of WI; curves would tend to converge when WI becomes bigger. Before the converging point, the increasing floor reflectance can increase vertical daylight levels. The shallower are the atria, then the bigger the daylight levels. These trends explain a fact that the floor reflectance mainly influences the daylight levels on the wall of lower atria or lower walls of deeper atria.

For MODEL 7 (WI 1.5) with different floor reflectances, the simulated vertical daylight factors at the centre line on the wall are displayed in Figure 10. Similarly, the simulated data decay as an exponential function of WID. It is apparent that for WID < 0.75 (distance from the top equals to ¾ atrium width) the daylight factors on the wall are little influenced by the floor reflectance.

Design guidelines

From discussions above, some guidelines for supporting daylighting design in atria are following:

(1) On the wall of atria, the daylight level varies in terms of an exponential form from top to bottom.
(2) As the reflectance values are increased incrementally, the daylight levels on the wall in atria increase at a proportionally greater rate.
(3) Increasing the reflectance of the wall surface of an atrium could improve the daylight levels on the wall. The increasing magnitudes at the higher or middle positions are bigger than the lower positions on the wall of atria.
(4) Increasing the reflectance of the floor of an atrium could improve the daylight levels on the wall, especially for shallow atria or the lower parts around base in deeper atria wall.

(5) The wall area between two vertical lines at a distance of 30% atrium width from the corner has the largest daylight levels and has the biggest possibility to naturally light spaces adjacent to the atrium well.

THEORETICAL COMPARISON

Two different analytical theories were chosen to calculate the vertical daylight factors on the wall.

Average vertical daylight levels on the wall

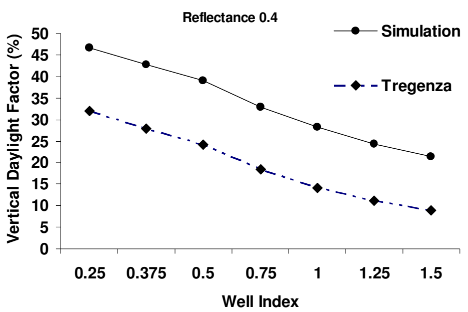

Figure 11: Comparison of average vertical daylight factor on the atrium wall.

Tregenza (1997) has developed one theory for atrium daylighting, which expresses daylight decays as an exponential form along the atrium surface. Two exponential equations have been used in calculating the average daylight factors across the whole wall in atria with different WI. Figure 11 shows the comparison of the values between simulated data and calculated data by the equations. For atrium with a WI range of 0.25 to 1.5 and a uniform surface reflectance 0.4, the theory underestimates the simulation with an average relative variation of 45% (taking simulation as reference). The maximum relative variation of them is less than 60%. But, it is clear that the two curves have a similar form or trend. The difference might be explained by the calculation grid setting on the wall in simulations, which did not cover every part of the wall surface like theoretical calculations. So, the simulated value is just the average of values at grid intersections. Furthermore, a similar investigation concerning the theory occurred in a report (Laouadi and Atif, 2006), which indicated some similar deviations when comparing the simulations using a zonal model with calculations by the theory. The authors pointed out that the underestimate is due to the fact that the vertical daylight factor in Tregenza's model is deduced from the horizontal daylight factor at a given height using constant parameters. In real atria, the daylight level, nevertheless, dramatically varies across the wall.

Vertical daylight levels at the centre lines

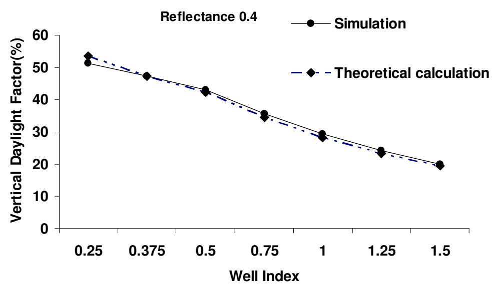

Figure 12: Comparison of vertical daylight factor at the centre line on the atrium wall.

Several theoretical formulae quoted by Littlefair in a review (2002) were used for the calculation of vertical daylight factor at the centre line on the atrium walls. The formulae include two parts: sky component and internal reflected component. The first part for sky component calculation came from an earlier work on horizontal skylights (Seshadri, 1960). Figure 12 shows the comparison of vertical daylight factor between simulation and the theory. For atrium with a WI range of (0.25, 1.5) and a uniform surface reflectance 0.4, the simulated data are very close to the theoretical calculations, which again enhance the validation of simulation.

CONCLUSION

In this study the impact of well geometry and surface reflectance on vertical daylight level in square atria under a CIE standard overcast sky has been investigated. By reviewing some previous applications and comparing the outputs from scale model measurements, the predicted vertical daylight levels from Radiance simulations were shown to be accurate. More simulations to determine vertical daylight levels for a much wider geometric and reflectance range of atrium models were then performed. In terms of the reflectance of wall and floor, the vertical attenuation and horizontal distribution of daylight level on atrium walls have been analysed and some guidelines have been presented. Finally, analytical expressions for vertical daylight level have also been introduced to compare with the Radiance simulations.

These conclusions are obviously limited to the specific geometries (e.g. square plan). The atria with asymmetric plans like rectangle will be studied in the next stage. Furthermore, the relationship between the vertical daylight level on the wall and the horizontal daylight level on the working plane inside adjacent rooms will be another topic to be investigated.

REFERENCES

Aizlewood M. 1995. "The daylighting of atria: a critical review." ASHRAE Transactions 101, pp 841-857.

Aizlewood M., Butt J., Isaac K. and Littlefair P. 1997. "Daylight in atria: a comparison of measurement, theory and simulation." Proceedings Lux Europa. Amsterdam, Netherlands.

Boubekri M. 1995. "The effect of the cover and reflective properties of a four-sided atrium on the behaviour of light." Architectural Science Review 38, pp 3-8.

Calcagni B. and Paroncini M. 2004. "Daylight factor prediction in atria building designs." Solar Energy 76, pp 669-682.

Fontoynont M., Laforgue P., Mitanchey R., Aizlewood M., Butt J., Carroll W., Hitchock R., Erhorn H., De Boer J., DirksMöller M., Michel L., Paule B., Scartezzini J-L., Bodart M and Roy G. 1999. "Validation of daylighting computer programs." IEA SHC Task 21/ ECBCS Annex 29, Nov.

Hung W. and Chow W. 2001. "A review on architectural aspects of atrium buildings." Architectural Science Review 44, pp 285-296.

Littlefair P. 2002. "Daylight prediction in atrium buildings". Solar Energy 73, pp 105-109.

Laouadi A. and Atif M.R. 2006. "Daylight availability in top-lit atria: prediction of skylight transmittance and daylight factor." Report NRCC44975, National Research Council Canada. Ottawa, Canada.

Laouadi A., Reinhart CF. and Bourgeois D. 2008. "Efficient calculation of daylight coefficients for rooms with dissimilar complex fenestration systems." Journal of Building Performance Simulation 1, pp 3 – 15.

Mardaljevic J. 1995. "Validation of a lighting simulation program under real sky conditions." Lighting Research & Technology 27, pp 181 – 188.

Oretskin B. L. 1982. "Studying the efficiency of light wells by means of models under artificial sky." The 7th passive solar conference. Knoxville, USA.

Roy G. 2000. "A comparative study of lighting simulation packages suitable for use in architectural design." Report of school of engineering, Murdoch University. Rockingham, Australia.

Seshadri T. N. 1960. "Equations of sky component with a CIE standard overcast sky." Proc. India Academy of Sci 57A, pp 233–42.

Sharples S. and Lash D. 2004. "Reflectance distributions and vertical daylight illuminances in atria." Lighting Research & Technology 36, pp 45-57.

Sharples S. and Lash D. 2007. "Daylight in atrium buildings: A critical review." Architectural Science Review, 50, pp 301-312.

Samant S. and Yang F. 2007. "Daylighting in atria: the effect of atrium geometry and reflectance distribution." Lighting Research & Technology 39, pp 147-157.

Tregenza P. 1997. "Daylight attenuation in top-lit atria." Lighting Research & Technology 29, pp 151-157.

NOMENCLATURE

w: atrium width; [mm]

l: atrium length; [mm]

h: atrium height; [mm]

y: the distance from the top edge; [mm]

WI: well index

$$WI = \frac{h(w+l)}{2wl}$$

WID: well indexed depth

$$WID = \frac{y(w+l)}{2wl} \quad \text{(rectangular atrium)}$$

$$WID = \frac{y}{w} \quad \text{(square atrium)}$$

DF_v: vertical daylight factor

IRC_v: vertical internal reflected component

Table 1: Atrium model and surface reflectance values (Sharples and Lash, 2004)

Model No.	**1**	**2a**	**3a**	**4a**	**5a**	**6**
Surface configuration	black	Wall:1 black band 1 white band Floor: black	Wall:2 black bands 2 white bands Floor: black	Wall:3 black bands 3 white bands Floor: black	Wall:4 black bands 4 white bands Floor: black	Wall:white Floor:black
Area-weighted reflectance	0.02	0.29	0.29	0.29	0.29	0.57

Table 2: Atrium model configurations and WI and WID values

	Model dimension and WI				**WID (MODEL7)**	
No	**w**	**l**	**h**	**WI**	**y**	**WID**
MODEL 1	200	200	50	0.25	50	0.25
MODEL 2	200	200	75	0.375	75	0.375
MODEL 3	200	200	100	0.5	100	0.5
MODEL 4	200	200	150	0.75	150	0.75
MODEL 5	200	200	200	1	200	1
MODEL 6	200	200	250	1.25	225	1.125
MODEL7	200	200	300	1.5	250	1.25