

TripleSave – The Investigation and Monitoring of a Combined Natural Daylighting and Stack Ventilation System.

G. Oakley, BSc(H), BA.

Dr S. J. Smith, BSc(H), PhD.

Dr L. Shao, BSc, PhD, MCIBSE.

Prof. S.B. Riffat, BSc, DipTech, MSc, DPhil, CEng, MIMechE, MCIBSE, MinstE, MASHRAE.

Institute of Building Technology, School of the Built Environment, University of Nottingham,

Nottingham, NG7 2RD, UK (Tel No: +44 115 846 6042; Fax No +44 115 951 3159)

e-mail: laxggo@hermes.nottingham.ac.uk or lazsjs@hermes.nottingham.ac.uk

Abstract: Increasing the use of natural daylight for lighting purposes in buildings may offer savings in total building energy consumption. One technique is the use of lightpipes that can not only bring light into otherwise inaccessible or dimly lit places, but also improve the internal environment without generating excessive heat. This investigation aims to develop a unit combining light pipe technology and passive stack ventilation by utilising the light pipe as an exhaust stack. The performance of two light pipes with diameters of 215 mm and 2.2 m in length, have been continuously monitored in two separate environmental chambers situated outdoors. Measurement of low velocity airflow rates and natural stack ventilation through the test chambers has been carried out using a tracer-gas method. The results show a good correlation between solar altitude/time of day, internal lux values and the external lux values. It has also been shown that by fitting a LCP panel to a light pipe, much higher levels of daylight can be transmitted. Temperature inside the chambers is controlled and stayed at approximately 20°C. Typical air change rate through the passive stack is about 8 air changes per hour in Winter. The results show that lightpipes are proficient devices for introducing daylight into buildings and reducing energy costs.

Introduction

As a result of the increased interest in renewable energy systems, natural ventilation and daylighting are being increasingly used in modern buildings. As well as the possible energy savings they could bring the systems can also create a healthier environment for occupants (1,2). Natural ventilation, including passive stack systems has been introduced into buildings across Europe. However, until now the two technologies have been separate systems and this paper describes a configuration that attempts to combine them both. It also forms part of a continuing study of lightpipe technology and monitoring being carried out by the University of Nottingham (3,4).

The technology investigated consists of concentric channels for both daylighting and natural ventilation. Figure 1 shows the system, where daylight enters the central stack (the lightpipe) and the outer channel allows passive stack ventilation

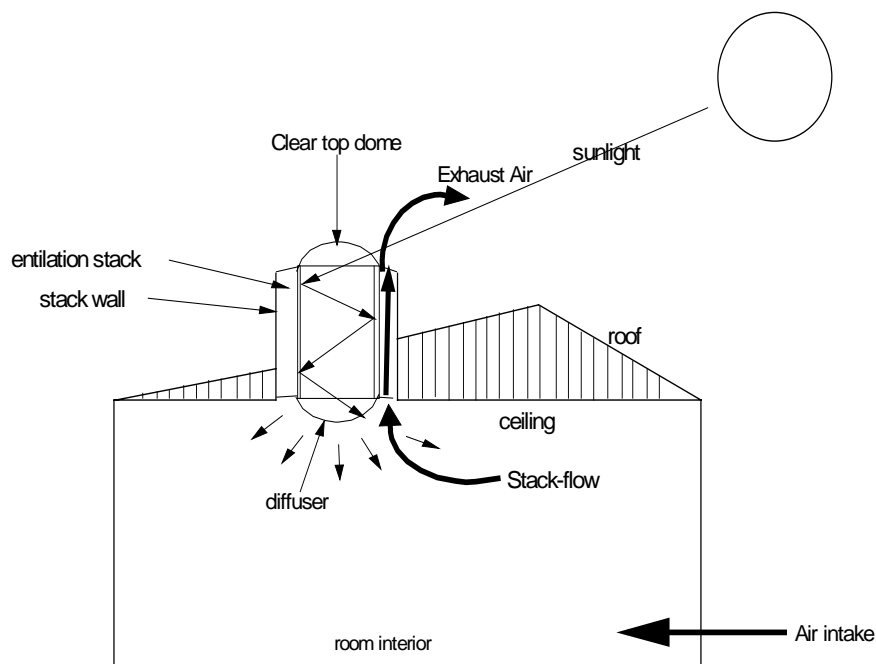


Figure 1: Combined daylighting and passive stack ventilation system.

Passive stack ventilation is driven primarily by the natural stack or convection effect by which warm air rises, entering a vertical (or near-vertical) column, to reach the colder outside air. The air inside a building is almost always warmer than that outside. So the warm air inside rises up the ventilation stack by a natural convection effect. Here experimental results are compared with theoretical analysis for ventilation flow rate through the test chambers.

Experimental Set-up

The Lightpipes

A description of lightpipes and a comparison of their performance in Europe can be found in the author's earlier paper (3).

The lightpipes were constructed by using Natralux *Spectralight 2000* film laminated on 0.5 mm aluminium sheets with a reflectivity of 95%. These came in 60 cm long pre-rolled pieces giving a diameter of 215 mm, and an aspect ratio of 10.2 (the ratio of lightpipe height over diameter). The vertical seams were taped, then two pieces of tube were attached to each-other. The exhaust air duct is a 250 mm ID ventilation tube that is concentric with the light pipe. The gap between the tubes is 15 mm and the diameter of the supply air duct was 100 mm. The pipes were then pushed inside stainless steel tubes 2.2 m high insulated with 100 mm polystyrene sheets The overall diameter being 452 mm for the whole tube (see Figure 2).

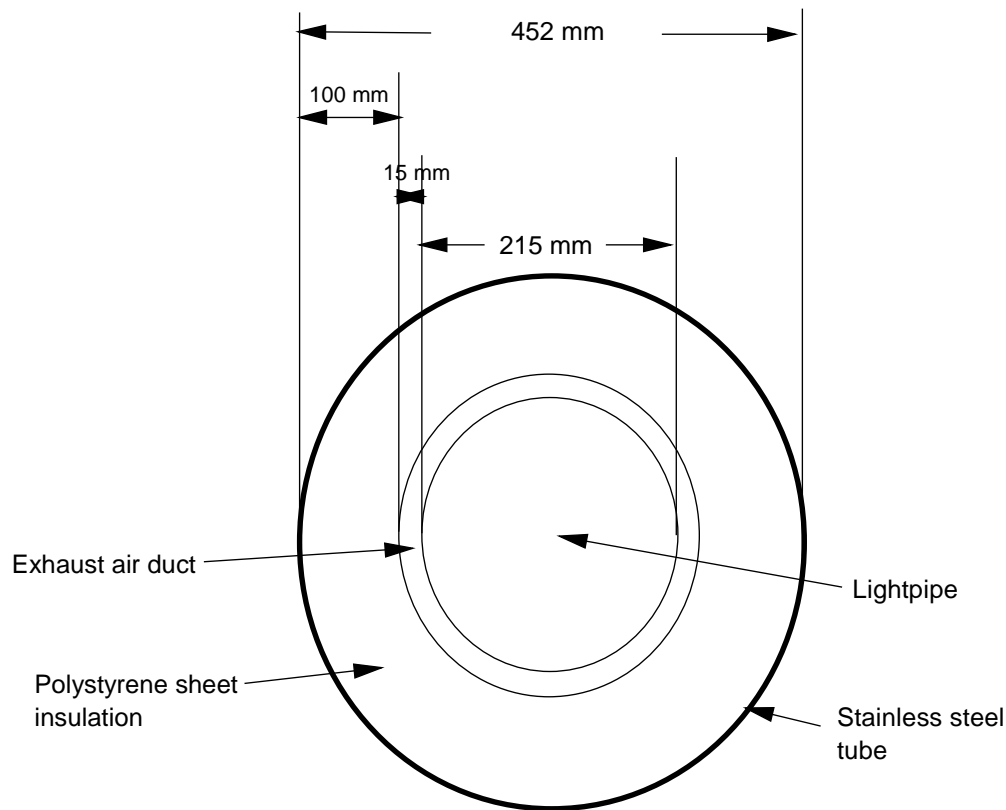


Figure 2: Cross-section of combined lightpipe and ventilation duct.

The Test Rig

Two experimental test chambers were constructed and located outdoors near the Institute of Building Technology at the University of Nottingham. The site was chosen to ensure that the direct solar radiation is not obstructed by trees, buildings or any other objects during the measurement period.

The dimensions of the test chambers are 1.3m x 1.3m x 1.3m (h, w and d). These were selected by taking into consideration the available space and minimum volume needed for reliable measurements. The interior frame is constructed from 15-mm chipboard painted white on the inside of the chamber to increase internal reflectivity.

The lightpipe was situated in the middle of the box and supported by a metal cradle (see Figure 3 below).

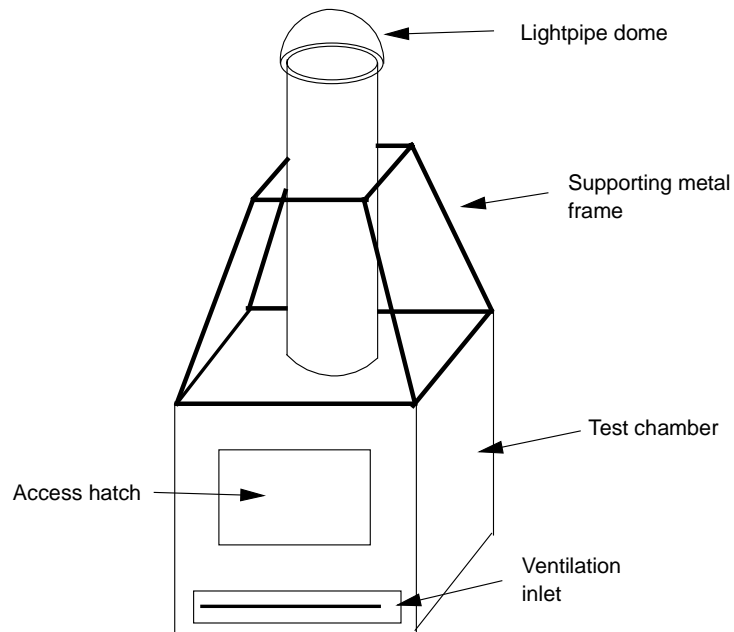


Figure 3: Test chamber and lightpipe supported by metal frame.

As the unit is situated outside it was insulated with 100-mm rockwool and covered with a waterproof rubber skin to give full protection from the weather.

The air inside the chambers was warmed by heating coils situated over an extra 50 mm thick insulation layer on the bottom of the box and covered by a 1 mm thick aluminium plate for fast and even distribution of heat.

Procedures for Daylight Measurement

The daylighting performance of the units is being tested under natural conditions, i.e. using solar radiation as a light source.

There are two illuminance sensors in each chamber:

- i) A sensor attached to the ceiling of the chamber, 5cm from the rim of the diffuser. The sensor faces downwards;
- ii) A sensor located placed on the floor of the chamber directly underneath the sensor on the ceiling;

And one external

- iii) A sensor located outdoors on an unobstructed horizontal plane for ambient daylight measurements.

The illuminance measurements were carried out using Hagner Digital E2X meters. They are based on a silicon diode photocell and capable of measuring illuminances in the range 0.01 to 200,000 lux. They have an accuracy of $\pm 3\%$ and a virtually perfect cosine correction curve. The meters connect to a remote photocell via a flexible lead, making it easier to read illuminance levels without blocking incident light reaching the photocell.

Laser Cut Panel

A Laser Cut Panel (LCP) is formed by laser cutting an acrylic panel so as to produce an array of transparent rectangular elements which transmit and deflect incident light by refraction and total internal reflection (Figure 4). When incorporated directly above a lightpipe the enhancement of illumination of the room below is the result of the deflection of low-elevation light more directly down the lightpipe to the ceiling aperture (5).

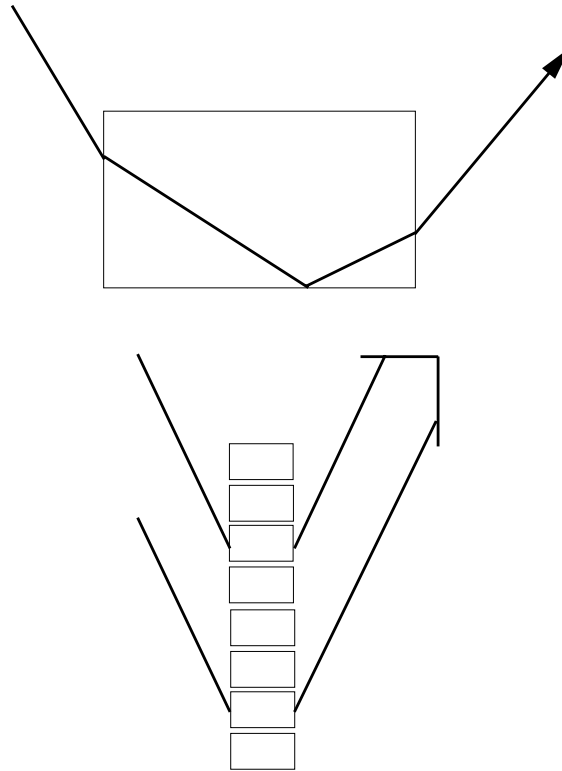


Figure 4: Light is deflected in a rectangular prismatic element by refraction and total internal reflection. An array of prismatic elements forms a light-deflecting panel. Such light-deflecting panels may be produced by forming a series of parallel cuts in a sheet of acrylic with a laser. A solid periphery is left uncut for support (5).

A Laser Cut Panel (LCP) was fitted inside the transparent dome at the top of the lightpipe of chamber 2 at a recommended angle of 30° above horizontal plane and facing south. Initial results showed that the LCP was inefficient during the summer except in early morning and late afternoon. This is due to the LCP being most efficient for solar angles of 30° or less. The LCP was then set to face South East for further tests, and the results can be seen in Figures 6 and 7.

Air Change Rate

For the accurate measurement of low velocity airflow rates through the test chamber the application of the constant injection tracer-gas method is used (6 & 7). A tracer-gas can be any commercially

available gas that is easily traceable in air, non-reactive with air, non-toxic and has a similar density as air so that good mixing with air is achieved. This investigation is carried out using the tracer-gas sulphur-hexafluoride [Sf_6]. Figure 5 shows the experimental set-up of the test rig. The tracer-gas is injected at a constant rate from a mass flow controller into each test chamber. The injection point is just behind the mixing fan, which faces down towards the centre of the chamber.

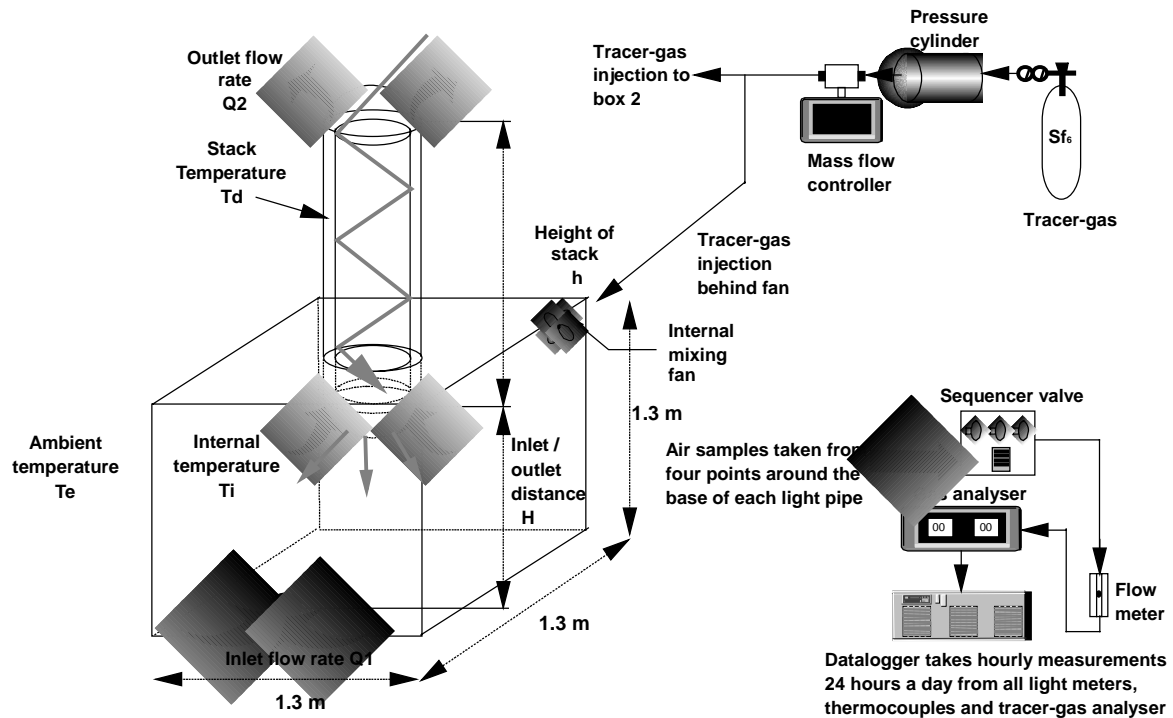


Figure 5 Tracer-gas analysis experimental apparatus.

After adequate mixing has occurred, samples of air are taken from each test chamber at the base of each light pipe close to the stack air inlet. Four samples were taken and mixed through a manifold giving an average value from the whole outlet area. The tracer-gas / air samples from each chamber are then time controlled before analysis by using a set of sequencer driven valves. The timed samples coincide with the datalogger so that values of tracer-gas concentration can easily be identified. The tracer-gas samples are pumped through the control valve and are filtered and the flow rate is controlled so that the gas analyser is not damaged.

Using the constant injection tracer-gas method if the injected flow rate Q_{tg} (m^3/h) is known and the concentration of tracer-gas around the stack air inlet C (ppm) is measured, the ventilation flow rate of air through the stack can be calculated using:

$$Q = (Q_{tg}/C) \times 10^6$$

Therefore the air change rate I (/h) for each test chamber could be calculated using :

$$I = Q/ V$$

Where V is the volume of the test chambers ($2.2m^3$).

The Tracer gas monitoring was carried out using a Brüel and Kjær 1302 Multi-Gas Analyser. The 1302 measurement principle is based on the photoacoustic infrared detection method, i.e. it can measure almost any gas that can absorb infrared light. The sequencer driven valve system mentioned above ensured that the 1302 only analysed one chamber's sample every half an hour. The 1302 has its own internal pump and filter and was purged using outside air between sampling.

Recording of Measurements

Measurements were taken at every fifteen minute intervals and averaged to give hourly results. Data from all sensors are recorded 24 hours a day, 7 days a week onto a Datataker 500 data logger. The

Datataker 500 is a microprocessor-based battery or mains powered data logger that measures inputs from most sensor types. Data is stored in battery backed RAM.

The data logger's internal memory is then downloaded once a week onto a laptop PC with DeLogger Plus Software. The data is then processed using MicroSoft Office Excel to produce spreadsheets and graphs.

Theoretical analysis of air change rate

The ventilation flow rate through a test chamber based on internal and external temperature difference can be calculated using:

$$Q = C_{di} A_i \sqrt{\frac{2g(\Delta T_p H + \Delta T_d h)}{T_e \left(1 + \frac{1}{k^2}\right)}}$$

Where C_{di} (=0.6) is the discharge coefficient of the air inlet, A_i [m^2] is the cross section area of the air inlet, g [m/s^2] is the gravitational constant, ΔT_d [K] is the internal/external temperature difference, H [m] is the vertical distance between the air inlet and the stack inlet, ΔT_d [K] is the temperature difference between the stack and the inside of the chamber, h [m] is the vertical height of the stack, T_e [K] is the external temperature and k is the overall loss coefficient (8, 9, & 10).

k can be calculated using :

$$k = \left(\frac{C_{do} A_o}{C_{di} A_i} \right)$$

Where C_{do} and A_o [m^2] are the discharge coefficient and the cross section area of the ventilation stack respectively. The value of C_{do} corresponds to that for a long duct and will generally lie within the range 0.3 to 0.7 depending on several factors, e.g. Reynolds number, and inlet shape (10). The value of C_{di} can be taken as 0.6 because it is a sharp-edged opening (10).

Therefore the corresponding theoretical air change rate for the test chamber can be calculated using :

$$I = Q / V$$

Where V is the volume of the test chamber [$2.2m^3$].

Results & Discussion

Figure 6 shows a typical set of results obtained in Summer with the LCP not fitted to any of the two chambers which exhibited very similar performance characteristics. The ratio of internal illuminance to external illuminance achieved was approximately 16%. This is consistent with the reflectivity of 95%.

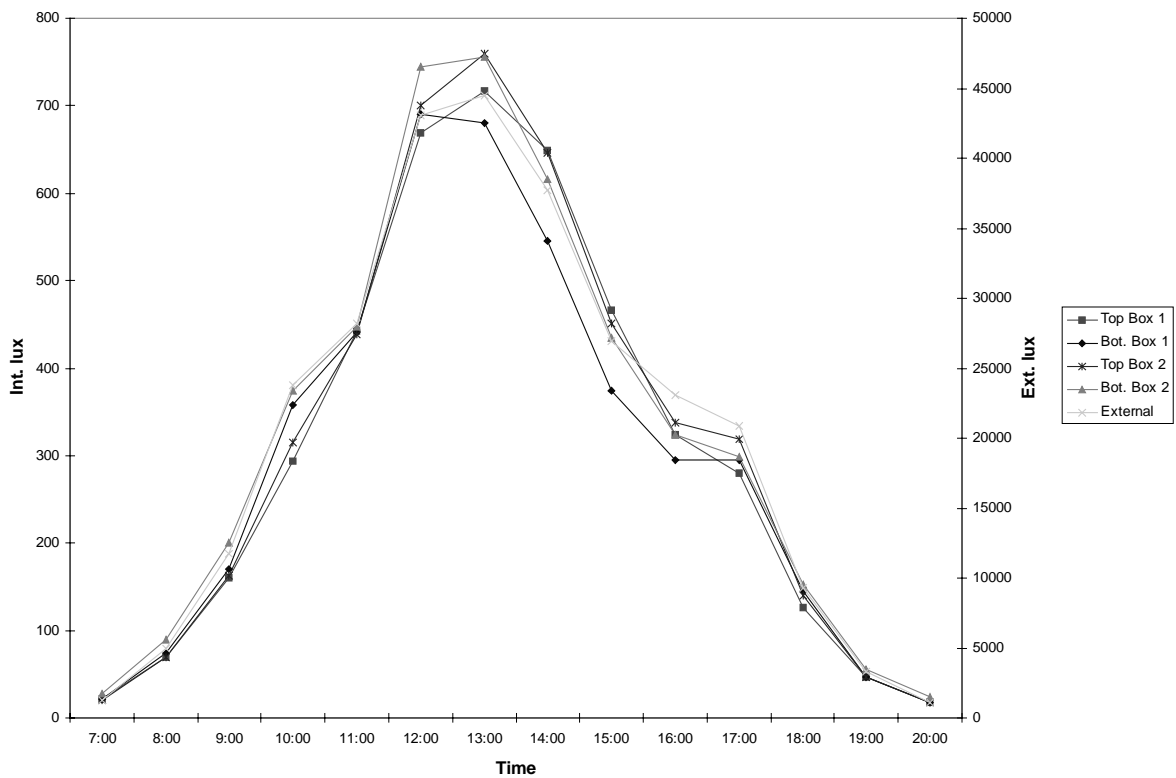


Figure 6: Lightpipe performance on 27th August 1999.

Figure 7 shows the illuminance values from both chambers on the 18th January 2000. It illustrates that chamber 2 which was fitted with the LCP panel received far more between 9-11 am with a definite peak at 10:00 am. The higher illuminance values were obtained in Chamber 2 for both ceiling and floor measurement points. The large difference between ceiling and floor values is probably due to the illuminance distribution patterns on the floor on sunny days.

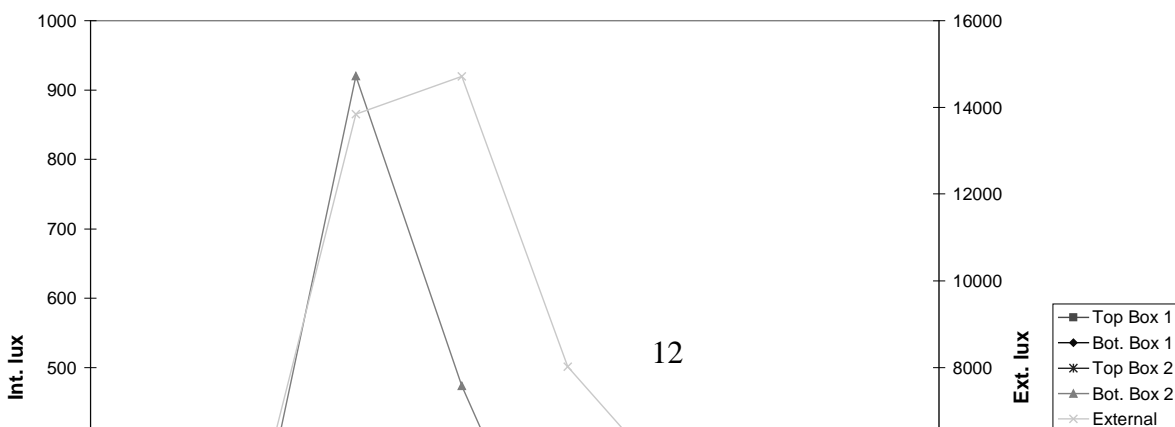


Figure 7: Illuminance values on 18th January 2000.

Figure 8 shows illuminance values for the week dated 17th-23rd January 2000 with clear peaks about the same time every morning (10:00 am). The bottom sensor in chamber 2 appears to be receiving approximately 800 lux more than chamber 1, and the top sensor approximately 200 more lux. However, after midday the performance of chamber 2 is less than chamber 1, probably due to the fact that the LCP faces SE and the optimum solar altitude for the LCP orientation is reached at 10 am. Further tests are to be carried out with the LCP facing other directions as part of the investigation to evaluate its performance.

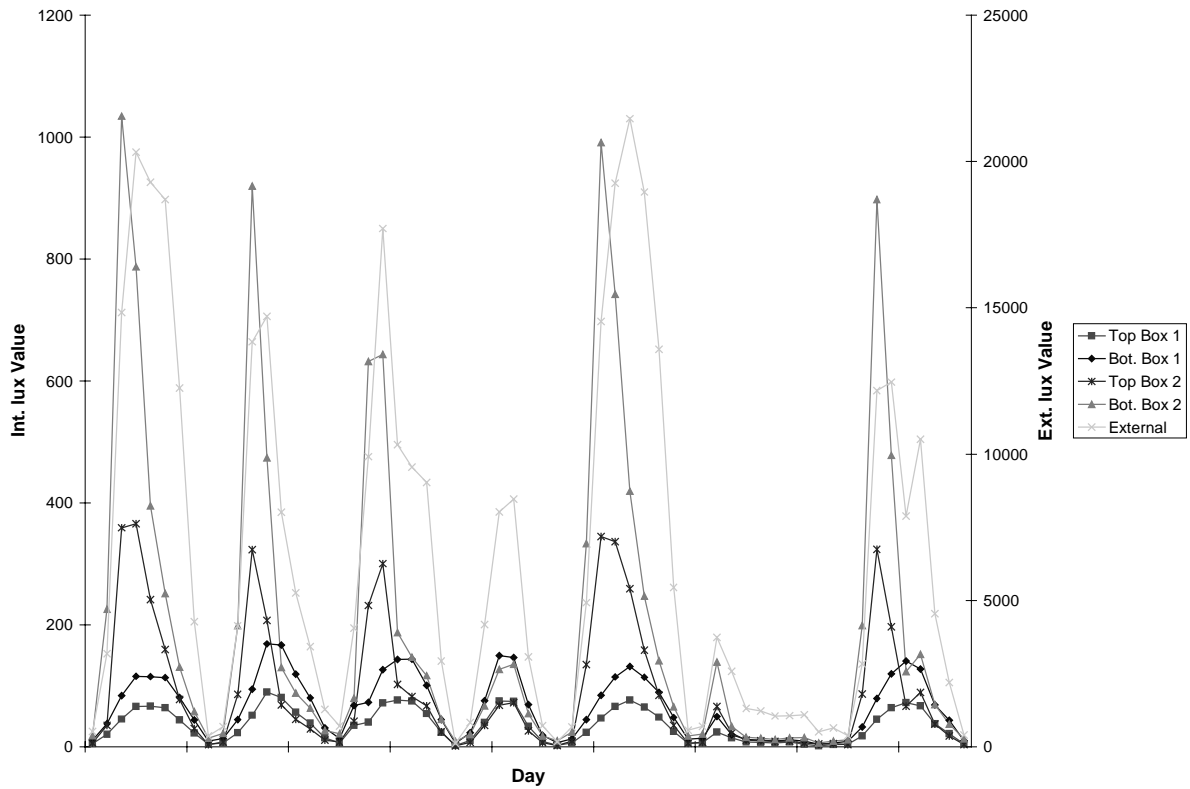


Figure 8: Illuminance values from both chambers for the week 17th-23rd January 2000.

Figure 9 shows average daily average daily illuminance values for the period March 1999-February 2000. The polynomial trend line shows a good correlation between time of year and the average amount of daylight. The figure also shows that the highest peaks during the summer are usually from the bottom sensors, which is expected as they receive more direct light rather than the diffused light that reaches the top sensors. Also noticeable are the high peaks from the sensor at the bottom of chamber 2 after November when the LCP was fitted.

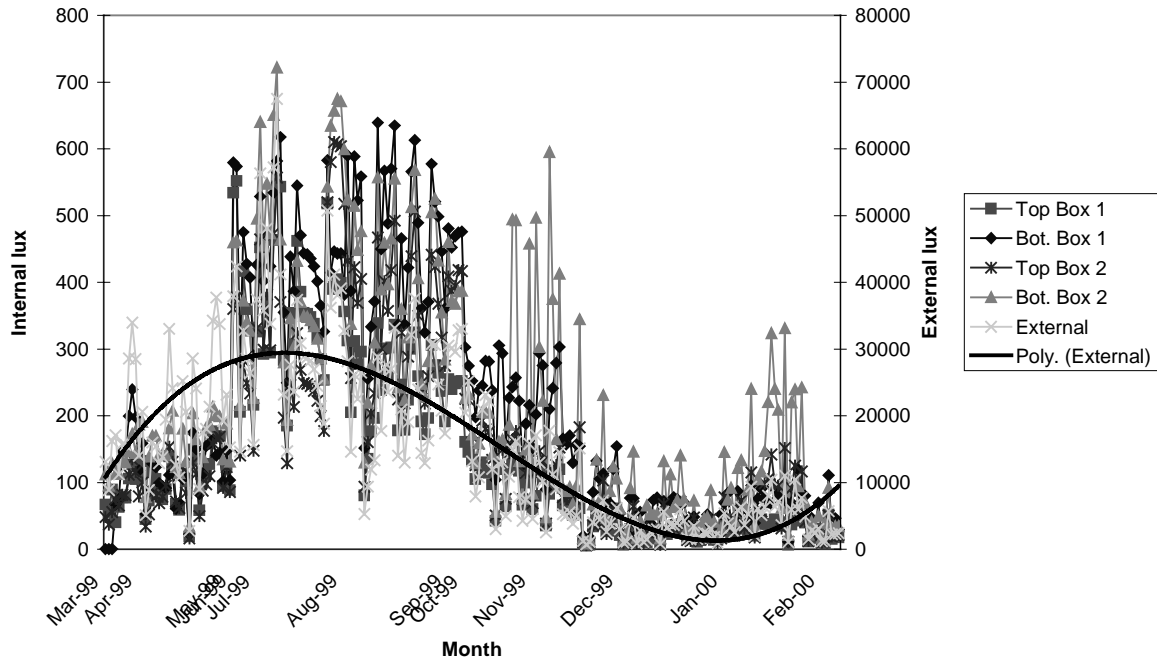


Figure 9: Average daily figures for the whole study period.

Air Change Rate

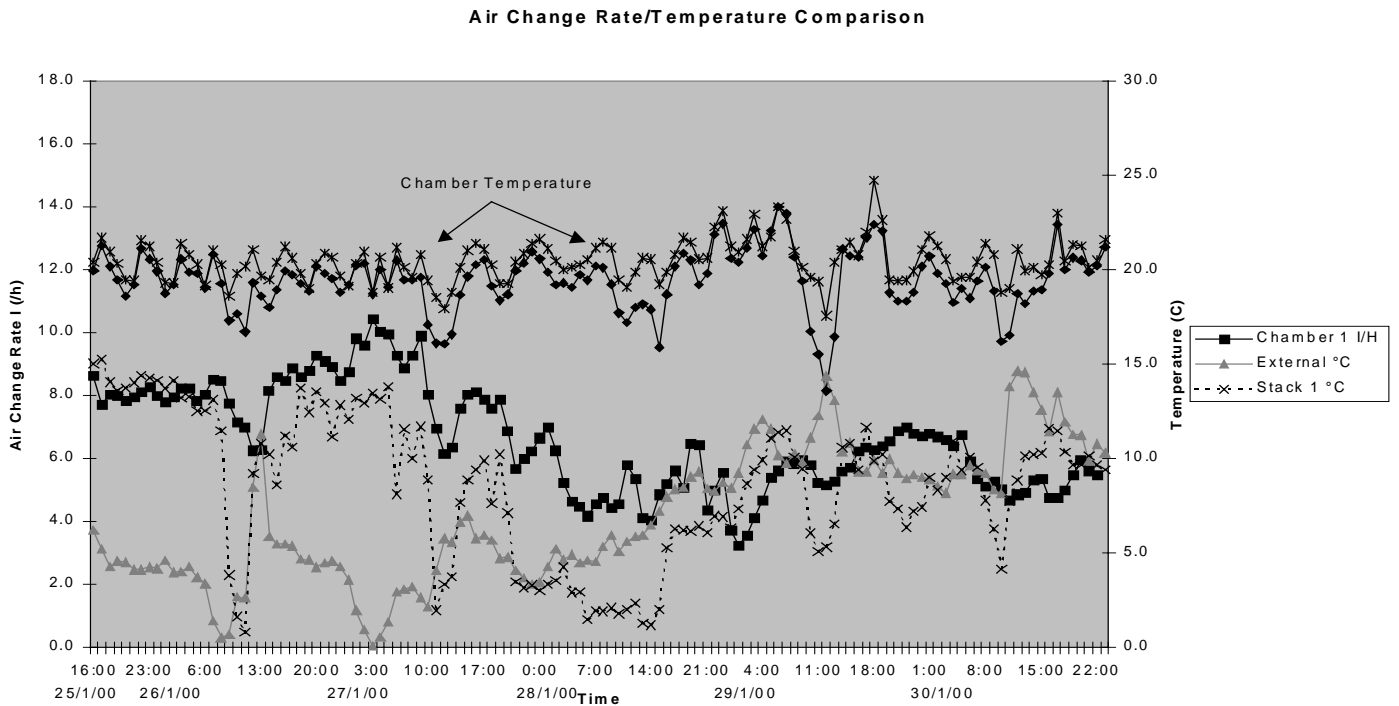


Figure 10: Air change rate and chamber temperatures for a 5-day test period.

It can be seen from Figure 10 that for an internal temperature of about 20 °C, as the external temperature reduces the air change rate increases due to the increase in stack effect. The air change rate also reduces with an increase in external temperature. It can also be seen that generally as the stack effect is increased then the stack temperature can be seen to increase because of an increased flow rate of warm air leaving the chamber.

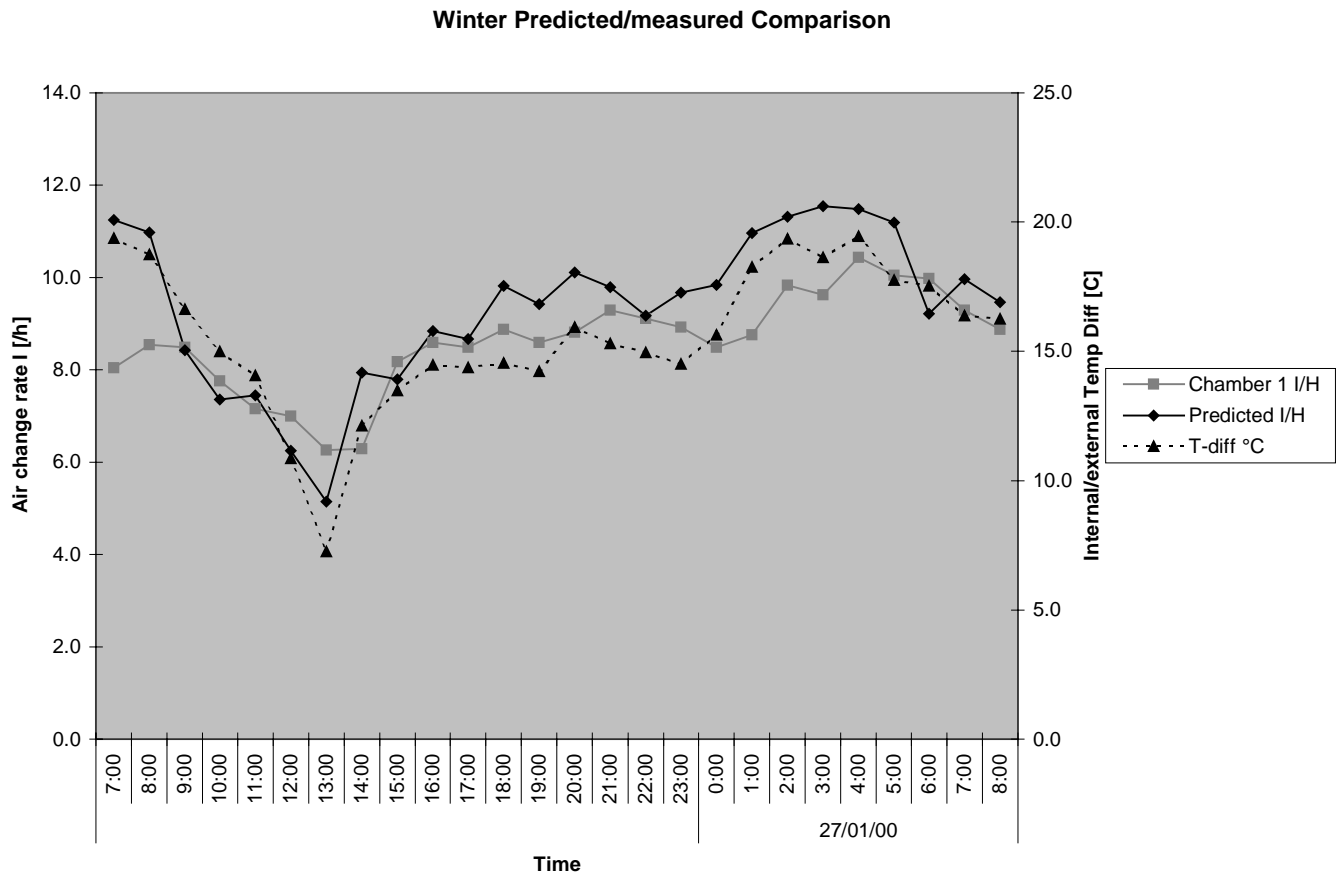


Figure 11: Comparison of predicted (theoretical) and measured (tracer-gas) air change rates during 26th-27th Jan 2000.

Figure 11 shows the comparison of predicted (theoretical) and measured air change rates of the test chamber based on the range of internal/external temperature differences experienced during a 24 hour test period.

It can be seen in Figure 11 that the measured air change rate for the test chamber is in good agreement with theoretical prediction for the range of temperature differences experienced. The theoretical prediction of air change rate for a temperature difference of 2 °C for a typical period in Summer is approximately 4 air changes per hour.

The effect of wind speed and direction has also been monitored and the following conclusions can be made. Although the wind speed and direction is theoretically supposed to have an outcome on air change rate, no significant effect could be observed in this study. However it was observed that on particularly “gusty” days when the wind was strong and its direction changed frequently, there was a significant drop in stack temperature of about 10 °C. This occurred over a very short period and recovered quickly. In addition, small pockets of air driven by gusts of wind into the stack had very little effect on the average air change rate. This also indicates that the stack flow is predominantly driven by the difference between internal and external temperatures and sudden changes in stack temperature have little effect.

Conclusion

Two experimental chambers have been built at the University of Nottingham to test a combined light and passive stack ventilation system. With this combined system an internal to external illuminance ratio of approximately 16% has been obtained. It has also been shown that by fitting a LCP panel to a light pipe, we can achieve much higher levels of daylight being transmitted, up to 800 lux more at certain times of the day. With the application of the constant injection tracer-gas method for measuring ventilation flow rates, it has been shown that 8 air changes per hour has been achieved with the natural stack effect. It has also been shown that there is good agreement between predicted (theoretical) values for the air change rate and the measured air change rates for the various internal and external temperature differences found in Winter. Using the combined weather monitoring

system it was discovered that the wind speed and direction had little effect on the test chamber air change rate.

Acknowledgements

The authors and the Institute of Building Technology would like to thank the European Commission for the EU Joule Program and its funding for this investigation.

References

1. Bouchet B and Fontoynt M: 'Daylighting of underground spaces: design rules', *Energy and Buildings*, 23(3), pp293-298, 1996.
2. Liberman J: 'Light – Medicine of the future', Bear & Company Publishing, 1991.
3. Oakley G, Riffat S & Shao L: 'Daylight performance of lightpipes', *CIBSE Conference Proceedings* pp158-174, October 1999.
4. Smith SJ, Riffat S, Shao L & Mualim AA: 'Evaluation of dichroic material for enhancing lightpipe natural ventilation and daylighting in an integrated system', *Applied Energy*, Vol. 62, No 4, pp253-266, 1999.
5. Edmonds IR, Moore GI, Smith G & Swift PD: 'Daylighting enhancement with lightpipes coupled to laser-cut light-deflecting panels', *Lighting Res. Technol.* 27(1), pp27-35, 1995.
6. Shao L & Riffat S: 'Tracer-gas mixing with air: effect of tracer species', *Applied Energy*, Vol. 49, pp197-211, 1994.
7. Shao L, Sharples S & Ward IC: 'Tracer-gas mixing with air', *BSE&T*, Vol. 14, No. 2, 1993.
8. Etheridge D W. Internal communication, Institute of Building Technology, Nottingham.
9. Etheridge D W. Unsteady flow effects due to fluctuating wind pressures in natural ventilation design - mean flow rates. *Building and Environment* 35(2), 111-133, 2000.
10. Etheridge, D. W. and Sandberg, M. (1996). *Building Ventilation: Theory and Measurement*, John Wiley & Sons, Chichester, UK, 720pp. ISBN 0 471 96087 X