AIR FLOW CHARACTERISTICS THROUGH MODULATED LOUVERED WINDOWS.

A A Maghrabi* and S Sharples**
*Department of Architecture
University of Sheffield, Sheffield, S10 2TN, United Kingdom
tel: (0114) 222 0399
fax: (0114) 279 8276
e-mail: apr95aam@sheffield.ac.uk

**School of Construction
Sheffield Hallam University, Sheffield, S1 1WB, United Kingdom
e-mail: s.sharples@shu.ac.uk

ABSRACT This study investigated the pressure flow characteristics over a number of full-scale modulated louvered windows (MLW). The various MLW parameters included louver inclination angle (θ), depth (L), aperture (d) and the ratio of aperture/depth (d/L%). Airflow models were developed using both power law and quadratic model equations. By examining the coefficient of determination (r^2) for both model equations, it was evident that the quadratic model equation suggested the best curves fit. The pressure flow characteristics as a function of louver inclination angle (θ) in conjunction with (d/L) were presented in dimensionless form. It was concluded that the pressure flow characteristics could be controlled if proper configurations of MLW were to be chosen.

1 Introduction

Airflow within and around buildings has been a rich topic of research for many years. Hence several investigations have been carried out on the mechanism of airflow through buildings and- further - on various parameters governing air motions indoors. The Modulated Louver Windows (MLW) have been used for centuries as tool to achieve thermal comfort in buildings by natural means. Although the body of literature pertaining to the MLW dealt with its solar control performance, the optimization of its various dimensions and configurations in relation to ventilation is far from being satisfactory. On the same hand, available studies were limited in scope (Yakubu & Sharples 1991, Tsangrassoulis et al. 1997, Pitts & Georgiadis 1994). In this context, the design of window acquires special importance as air mainly flow inside buildings through its apertures. Entire parametric studies are still needed to investigate the pressure and velocity drops as functions of MLW various components.

Nevertheless, most of the available CFD packages deal with ventilation aspects in simplistic ways and may not necessarily reflect complexities occurring in physical circumstance. Furthermore, theoretical representations of airflow passing through a window could not be simplified. Calculation methods in building ventilation tend to rely upon simple experimental data and general assumptions since precise calculations of unsteady flow characteristics of openings within building are rarely known. Hence it is more preferable to undertake laboratory measurements as the *steady flow characteristic* is a significant parameter to establish any ventilation measurements (Etheridge & Sandberg 1996).

This paper presents the full-scale of pressurisation laboratory experiment carried out at the School of Architecture, University of Sheffield to investigate the influence of various MLW configurations on pressure flow characteristics (ΔP) under controlled volume-flow rates (Q). These configurations included louver inclination angle (θ), depth (L), gap between louver blades or aperture (d) and the ratio of aperture/depth (d/L). The ratio was developed to establish a non-dimensional relationship between (d) and (L). It ranged from 0.5 in which half distance of the louver depth will overlap the one underneath when MLW considered totally closed up to 1 where the outer edge of the louvre will just overlap the inner edge of the louver underneath. It will show the variations of differential pressure across inner and outer volumes as a function to the above-mentioned variables. The experimental work is reviewed and followed by the analysis and discussion of results based on quadratic and power law model equations.

2 Methodology

2.1 Modulated louvered window configurations

Ten models of full-scale MLW with different configurations were made for further analysis. Louvers could be adjusted to any pre-set inclination angle ranging from +60° to –60° at intervals of 15°. They were made of smooth pine wood with fixed frame dimensions (0.48m height and 0.32m breadth). Every model has its own mechanism that allows louvers to incline from 0° angle- when the window is totally open- up to the degree, say (θ), when the outer edge of the louver will overlap the inner edge underneath ($d \cong 0$). Three louvres' depths (L) were chosen; 0.04, 0.06 to 0.08m. The six different gap dimensions (d) chosen were 0.01, 0.02, 0.03, 0.035, 0.05 and 0.07 m (Fig.1).

No	Depth L *(m)*	Aperture d *(m)*	Number N	Ratio d/L *(%)*
1	0.04	0.01	24	0.5
2	0.04	0.02	16	0.75
3	0.04	0.03	12	1
4	0.06	0.02	16	0.5
5	0.06	0.03	12	0.67
6	0.06	0.035	11	0.75
7	0.06	0.05	8	1
8	0.08	0.03	12	0.5
9	0.08	0.05	8	0.75
10	0.08	0.07	6	1

The MLW configurations

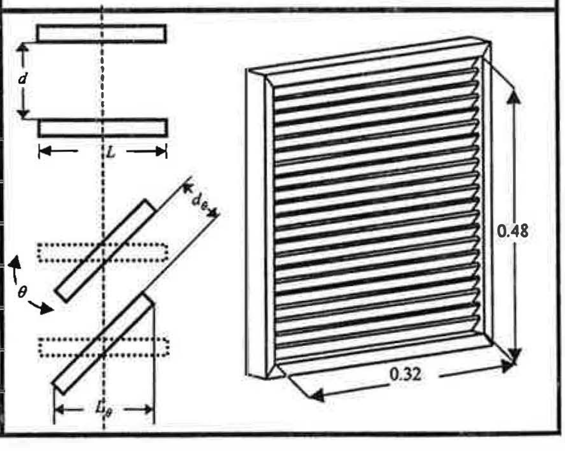

Fig.1 The modulated louvred window (MLW) various configurations

2.2 Experimental set up

A pressurisation chamber of 1×1×2 m with a volume of 2 m^3 was made to represent the environment where internal pressure would be recorded. There was no need to measure external pressure through a shield box (Baker et al. 1987). Models were fitted later on the front panel of the chamber. The other end was equipped with a laminar volume-flow meter device and connected with four extraction fans from which volume-flow air (*Q*) was recorded. A small door on the side elevation of the box was made to enable tilting louvers to the desired inclination angle. Two digital micromanometer devices were used and adjusted to record pressure and volume-flow air at four readings per second. The first was connected to the volume flow-meter device to record the volume-flow of air passing through. Similarly, the differential pressure across the louvers was measured using other device. Both devices ranged from 0-199 *Pa* and operated with self-calibrating devices to ensure compensation for zero-drift, making them accurate enough to measure small pressure differences with an accuracy error of less $\pm 1\%$ as quoted by the manufacturers. A data-logger was used to transfer the data to a computer.

A number of routine measurements and calibrations were made prior to the final analysis. The proper sealing of the pressurisation chamber was intended to minimise infiltration arising from depressurisation and resulted in higher-pressure drops occurring at extremely low volume-flows. For precision, this low infiltration rate was considered to determine the actual volume-flow passing the MLW.

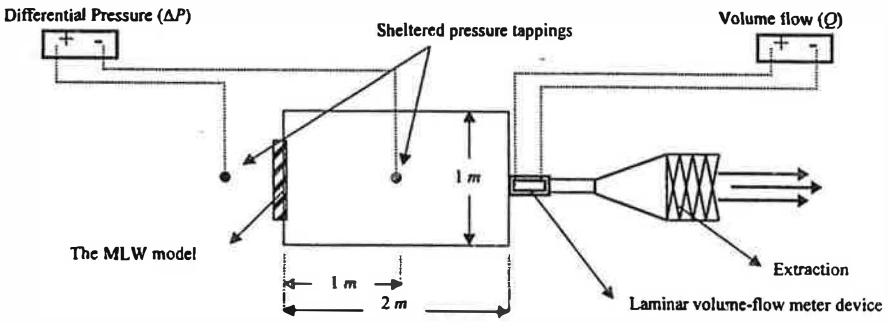

Fig.2 Schematic diagram of the experimental setup

Internal and external pressure tappings were positioned away from the influence of flow through the opening. Pressure tappings were positioned at six different locations in the pressurisation chamber before the centre location was finally recommended. Also an adjustment had been made for both micromanometers and software to give an average reading of various timings (1, 2, 3 minutes respectively), at four readings per second each. The 2 minutes was found most appropriate as positive time was given for the flow to reach its steady state and to avoid any turbulence while recording was being made. The authors compared the current results with another study (Yakubu & Sharples 1991) carried out under similar circumstances but on a much smaller range of parameters. They found that the results in both cases were similar.

2.3 Measuring principles

Readings of both pressure and air volume-flow were transferred to the computer attached when the reading had stabilised and flow was considered in a *steady state*. In measurement, *steady flow characteristic* occurs when pressure difference across an opening pressure difference does not vary with time under a specific volume of fluid (Etheridge & Sandberg 1996). The fan speed was set to various extraction rates in order to create ranges of pressures for specified volume-flow rates of air. The prior step was repeated over a range of pressure drops obtained from the combined power of the 4 axial fans. Then, louvers were adjusted to the next desired angle and the above mentioned steps were repeated for each setting. The laboratory temperature was ensured to be about 20° C, the temperature that was programmed for both micromanometers.

3 Power law and quadratic model equations

The validity of the power law and quadratic model equations have been experienced by many researchers in ventilation studies to set standards for building envelopes, ventilation requirements and many other infiltration models. Both calculation methods have been broadly accepted and the debate as to which of the two is more valid is still on-going (Yakubu & Sharples 1991, Walker et al. 1998, Thomas & Dick 1953, Sherman et al. 1979, Dick 1950, Chand et al. 1988, Chand 1970). The power law function is expressed as:

$$\Delta P = a \cdot Q^n \quad (1)$$

where ΔP is pressure drop across crack [*Pa*], *a* is a constant proportional to the effective leakage area of the crack [$m^3/s\ Pa^n$], *Q* is the volume flow rate [m^3/s] and *n* is the exponent.

Alternatively, other researchers in the field apply the quadratic model equation. Etheridge (1997) prefers the quadratic equation method to determine the air infiltration. This formulation is expressed as following:

$$\Delta P = AQ + BQ^2 \quad (2)$$

where *A* is the flow coefficient for fully developed laminar friction losses [$(Pa\ s)/m^3$], and *B* is the coefficient of entry, exit and turbulent flow losses [$(Pa\ s^2)/m^6$].

Coefficients *A* and *B* are determined by the standard fluid mechanics principles:

$$A = \frac{12\mu z}{Ld^3} \quad (3)$$

$$B = \frac{\rho Y}{2d^2L^2} \quad (4)$$

where μ is the dynamic viscosity [kg/ms], *z* is the plate length [*m*], *L* is the depth of the plate [*m*], *d* is the gap thickness [*m*], ρ is the fluid density [kg/m^3] and *Y* is the a factor depending on crack geometry.

Substituting coefficients *A* and *B* into Eq. (2):

$$\Delta P = \left(\frac{12\mu z}{Ld^3}\right)Q + \left(\frac{\rho Y}{2d^2L^2}\right)Q^2 \quad (5)$$

However, inclination angle of louver (θ°) was not part of the two coefficient considerations. For MLW, pressure difference could be a function to vertical inclination angles of louver. Assuming two louver blades placed at a distance (*d*) with a depth (*L*) at initial inclination position (0°) when the two blades are perfectly horizontal as shown in Fig.1. When louvers initially were tilted positively or negatively to a determined inclination, say (θ), this would be accompanied with a decrease in the effective gap thickness between louvers (d_θ) and the depth of louver (L_θ). It is evident from the pressure difference for the parallel plate theory and when angle θ = 0° that $\Delta P = AQ + BQ^2$. Then ΔP_θ would be represented as follows:

$$\Delta P_{\theta} = \Delta P \cdot \frac{1}{\cos^4 \theta} \tag{6}$$

For ventilation research, some correlation is needed to identify the flow rates as a function in relation to pressure difference due to wind, stack effect, .etc, which is expressed as follows (Etheridge 1997):

$$Q = \frac{-A \pm \sqrt{A^2 + 4B\Delta P}}{2B} \tag{7}$$

These equations are called here to establish a comparison between the measured flow data with respect to theoretical formulations.

By examining the coefficient of determinations (r^2) of both model equations, it was evident that curves produced by quadratic equation were preferred particularly in models where the ratio (d/L>0.5). The coefficient of determination of latter ratios was 0.989. The smoother curves produced by quadratic formulation fitted the scattered data at both pressure limits (i.e. higher and lower ΔP). On the other hand, power law curves were gradually accepted as louvers were tilted to steeper angles ($\theta = \pm 60$) and caused an increased pressure drop due to pressurisation with a coefficient of determination (r^2) that ranged from 0.337 at $\theta = 0^\circ$ to 0.981 at $\theta = 60^\circ$. This Showed that power law curve fits was gradually improving from 0° to the maximum measured angle.

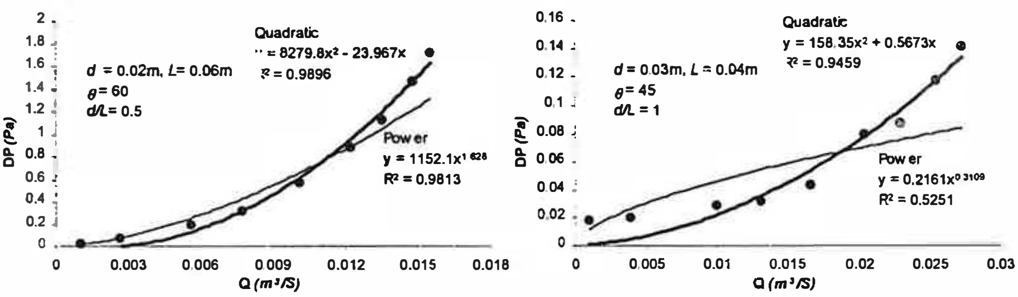

Fig.3 Regression curves produced by quadratic and power law model equations

However, representations of both coefficients evolved in the quadratic equation A (eq. 3) and B (eq. 4) could not be simplified theoretically due to number of factors. The first was related to physical complexities of flow characteristics passing through MLW various components. As mentioned earlier, these complexities could not be simplified theoretically. The second factor seemed more likely to relate to aperture of MLW. In 70% of models investigated, the aperture dimensions (d) were big enough for air to flow with no much resistance causing similar pressure drops for various d and L dimensions that are embedded in both coefficients. Similarly, the value of volume-flow of air as in equation (7) could not be simplified theoretically. This is merely due to the fact that the original format of equation was based on single crack theory. Thus it is assumed that for models with series of parallel cracks, the parallel plate theory would apply (Walker et al. 1998). Here, the total flow as the sum of number of cracks evolved could not be justified due to interference to flow caused by parallel cracks. This interference would differ from that resulted from single cracks. Another possible explanation was concerned with the inclination angle. The latter equation had no consideration to the inclination angle of plate. These added to others embedded in the coefficients A and B could be the possible answer for discrepancies found in theoretical representation of Q. Such corrections is beyond the scope of this investigation, and thus, further adjustments of the quadratic model equation would be required to fit variables that might not be embedded in both Q and the coefficients A and B equation formats.

4 Discussion

Differential pressure was measured aiming to establish an understanding of the flow characteristics whilst passing through MLW various components. The resultant pressure drops as function of louvers inclination angles (θ) was generally not significant except at inclination angle ($-45^\circ \geq \theta \geq +45^\circ$). Fig.4 shows the gap between curves produced by inclination $\theta = \pm 45^\circ$ and those below, i.e. $-30^\circ \geq \theta \geq +30^\circ$ where curves yielded towards lower pressure drops even at the highest volume-flow rate measured ($Q \cong 0.03$ m^3/s). This gap was even more distinguishable at inclination angle $-60^\circ = \theta = +60^\circ$ showing that inclinations at the latter pre-sets were the main parameters to cause significant pressure drop therefore. As far as the direction was concerned, variations found between positive and negative inclination angles were diminished and negligible (Fig.5).

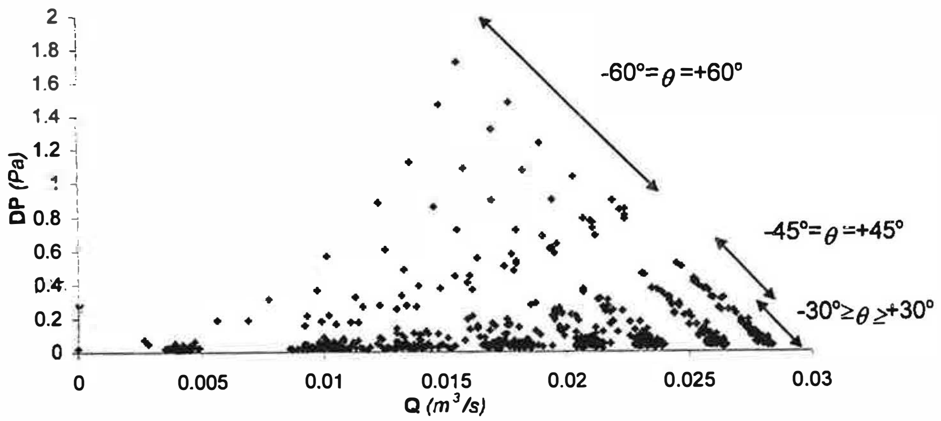

Fig.4 ΔP data as a function of inclination angles

The varieties in louvre apertures examined resulted in various pressure curves therefore. In cases where aperture $d \leq 0.035m$, higher-pressure drops was achieved compared with bigger dimensions. In the latter situation pressure records was diminished to lower readings (max. ΔP <0.45 *Pa*). Also, louvre apertures played a main role when accompanied with inclination angle. As louvers were tilted to steeper inclinations the dimension of the aperture, say (d_θ), was lessened accordingly causing reduction in pressure. As shown in Fig.5, ΔP would increase as aperture dimension would decrease. This was the fact for all MLW models examined. However, that was not the case with the variety of depths concerned. Depth of louvre was the least affecting variable in the resultant differential pressures though in some cases it positively functioned as motivate barrier to airflow (Fig.5). The number of louvres (N) in the same MLW model caused also some considerable pressure differences of air. As shown in Fig.5, these drops would occur as louvre number would be $N \geq 12$ blades.

Further, the relationship between d and L dimensions was established in the form of ratio d/L. Lower ratios of d/L showed an increased pressure drops than higher ones (Fig.5). At lower ratio *d/L*= 0.5, significant pressure drop was at $\theta = \pm 30^\circ$ whilst that significance occurred at $\theta = \pm 45^\circ$ when bigger ratios were present. In contrary, ΔP would be dimensionless at ratio *d/L*=1 no matter what other configurations of MLW were. As shown in Fig.6, this dimensionless relationship could not be established at $d/L \leq 1$.

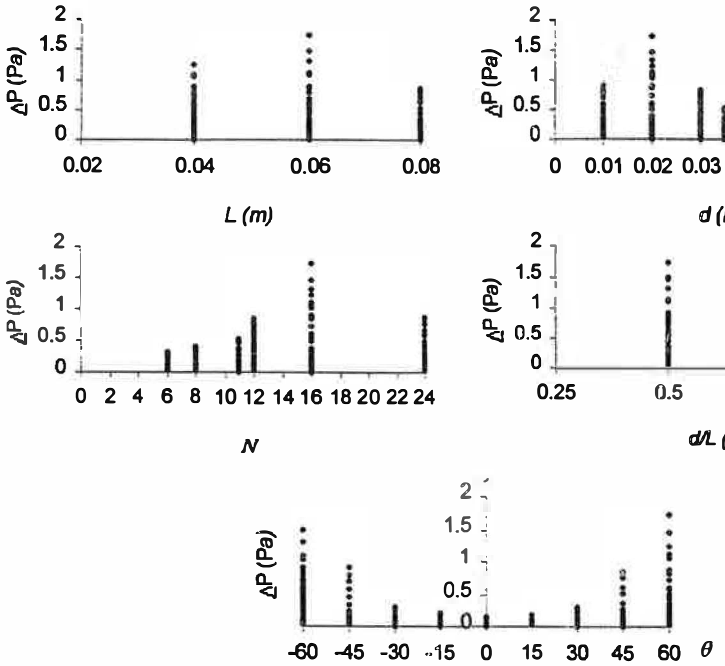

Fig.5 Differential pressures as function of various configurations of MLW

5 Conclusion

This study investigated the pressure flow characteristics over a number of full-scale MLW. The various MLW parameters included louvre inclination angle (θ), depth (L), aperture (d) and the ratio of aperture/depth (*d/L* %). The following points were concluded:

- The quadratic model equation suggested the best curves fits compared to that produced by power law regressions. The quadratic curves were in the form of: $\Delta P = AQ + BQ^2$. However, further adjustments of the theoretical representations of equation in the quadratic form would be required to fit other variables such as number of louvers and their inclination angles.
- The reduction in aperture area due to tilting louvre inclination angle upward or downward is the key variable to pressure drop. In contrast, louvre depth was found to be the variable with the least effect.
- Considerable pressure drop could not be achieved except at inclinations $-45^\circ \geq \theta \geq +45^\circ$. No major variations on drops were found between louvres positive and negative inclinations.
- The major enhancements in differential pressures were not due to individual variables (i.e. θ, d, L) but rather to combination of variables that would comprehensively describe ΔP. Thus, the expression of ratio (*d/L*) in conjunction with the inclination angles (θ) of louvers was a significant choice to comprehend the dimensionless changes in resultant pressures.

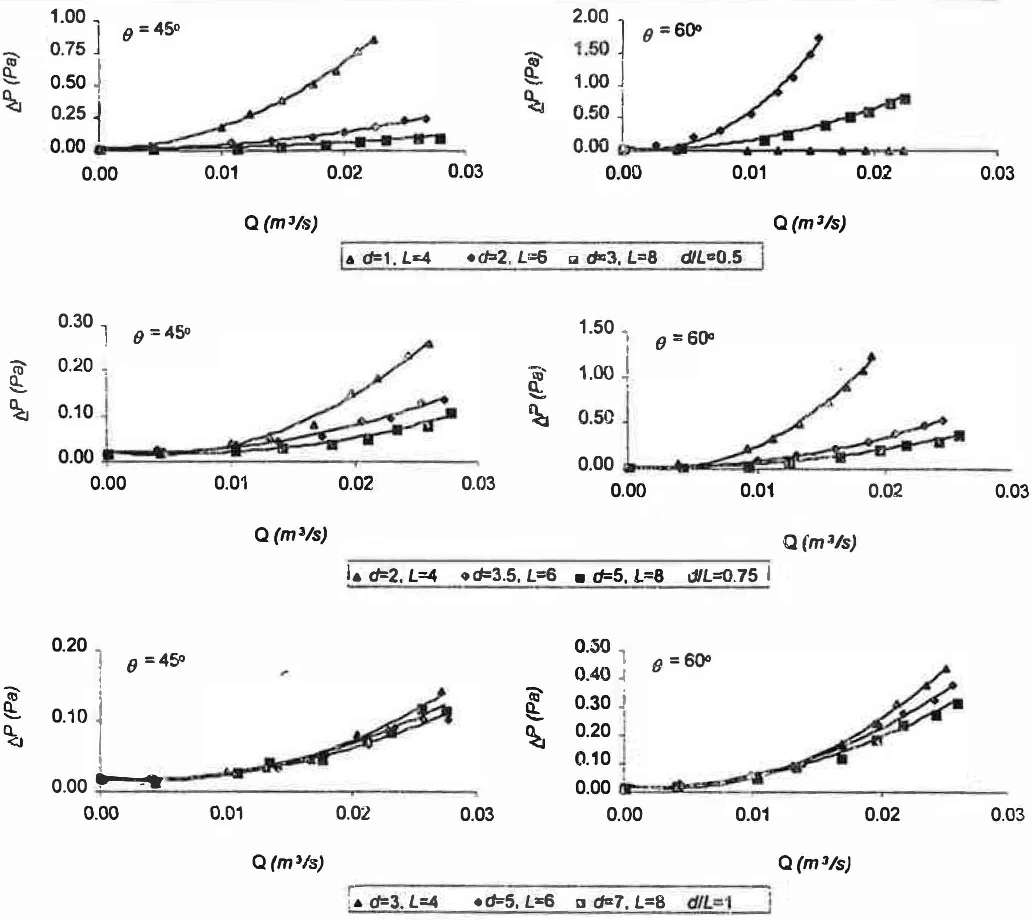

Fig.6 Differential pressures as function of various d/L ratios (0.5, 0.75, 1)

6 References

ASTM Standard E779 (1982): *Measuring air leakage by fan infiltration pressurisation method*, Annual book of ASTM standards 1418-1493.

Baker, P.H., Sharples, S. and Ward, I.C. (1987): Air flow through cracks. *Building and Environment* **22** (4):293-304. Great Britain: Pergamon Journals Ltd.

Chand, I., Bhargave, P.K., Sharma, V.K. and Krishak, N.L. (1988): Studies on the effect of mean wind speed profile on rate of air flow through cross-ventilated enclosures. *Architectural science review* **35**, 83-88.

Chand, I. (1970): Effect of the distribution of fenestration area on the quantum of natural ventilation in buildings. *Architect and Science Review* **13**, 130-133.

Dick, J.B. (1950): The Fundamentals of Natural Ventilation in Houses. *JIHVE* **18** 123-134.

Etheridge, D.W. (1997): A note on crack flow equations for ventilation modelling. *Building and Environment* **33**, 325-328.

Etheridge, D. and Sandberg, M. (1996): *Building Ventilation: Theory and Measurements*, first edn. John Wiley

Pitts, A. C. and Georgiadis, S. (1994): Ventilation air flow through window openings in combination with shading devices. 15th AIVC Conference 432-439 p. AIVC.

Sherman, M., Grimsrud, D.T. and Sonderegger, R.C. (1979): Low pressure leakage function of a building. LBL-9162, Lawrence Berkeley Lab.

Thomas, D.A. and Dick, J.B. (1953): Air infiltration through gaps around windows. *JIHVE* 462-463.

Tsangrassoulis, A., Santamouris, D., Asimakopoulos, D., (1997): On the ventilation and daylight efficiency of various solar shading devices. 18th Annual AIVC Conference 225-233 p. AIVC.

Walker, I.S., Wilson, D.J. and Sherman, M. (1998): A comparison of the power law to quadratic formulations for air infiltration calculations. *Energy and buildings* **27**, 293-299.

Yakubu, G.S. and Sharples, S. (1991): Airflow through modulated louver systems. *Building Services Engineering Research and Technology* **12** 151-155.