# PERFORMANCE EVALUATION OF NATURAL VENTILATION THROUGH WINDOWS WITH HORIZONTAL BLADE SHUTTERS

Shuqing Cui, Riccardo Issoglio, Juslin Koffi, Mohamed El Mankibi, Pascal Stabat, Dominique Marchio

Topic B4: Ventilation

# PERFORMANCE EVALUATION OF NATURAL VENTILATION THROUGH WINDOWS WITH HORIZONTAL BLADE SHUTTERS

Shuqing CUI[1,*], Riccardo ISSOGLIO[2], Juslin KOFFI[2], Mohamed EL MANKIBI[2], Pascal STABAT[1], Dominique MARCHIO[1]

[1]CES, Mines Paristech, Paris, France,
[2]Ecole Nationale des Travaux Publics de l'Etat, Vaulx-en-Velin, France

[*]Corresponding email: shuqing.cui@mines-paristech.fr

**Keywords:** Natural ventilation, Gas tracer, Shutter

## SUMMARY

The use of shutters can reduce the drawbacks of natural ventilation on intrusion risks and acoustic problems. However, when the shutters are used with single-sided ventilation, the air change rate is too deeply reduced. This study shows that the air change rate is maintained to acceptable values in cross-ventilation contrary to single-sided natural ventilation for horizontal blade shutters. An experimental investigation is carried out on a hotel room with or without shutter in Corsica, France. The air change rates are given out by the tracer gas technique using carbon dioxide. The concentration decay method is applied and the decrease of tracer gas concentration in the room is measured by 9 $CO_2$ sensors in various positions. Air change rates are given for different wind orientations and speeds. Even if the shutters reduce by 45% the window opening surface on one side, the air change rate can be kept up to 80% of that with a plain opening without shutter since it is limited by the other side window which has smaller opening surface.

## INTRODUCTION

Natural ventilation is an attractive solution for cooling buildings, but is often rejected because of intrusion risks or acoustic problems. (Cui et al., 2013) studied different designs of acoustic shutters seeking a trade-off between ventilation and noise attenuation. The air change rate (ACR) was evaluated by computational fluid dynamics (CFD) using Reynolds Average Navier-Stokes equations. The results showed that shutters could reduce from 60 to 80% the ACR while attenuating from 3 to 12 dB external noise compared to a fully opened window in the single-sided ventilation mode. Such reduction on the ventilation performance is hardly acceptable, leading to assessing if the cross-ventilation mode could broaden the frontier of using acoustic shutters.

As reported by many papers, the validation of numerical calculation is realized by scaled models and in-situ measurements (Chao et al., 2004, Stavrakakis et al., 2008, Hooff et al., 2012). The scaled models seem to be a good solution due to their low cost, easily controlled boundary conditions and strong repeatability. However, the in-situ measurements are indispensable as the tests are conducted in real conditions where wind turbulence and buoyancy effects are taken into account. A hotel room located in a gulf in Corsica, France has been chosen to be the test space, as shown in Figure 1.

In this study, it is decided to investigate experimentally how the ACR can be reduced in the case of cross-ventilation and single-sided ventilation when using of horizontal blade shutters.

**Figure 1. Hotel top view (upper). Loggia (bottom left). Entrance door (bottom right).**

## METHODOLOGY

### Air change rate measures

The ACR is a key indicator to understand ventilation performance. In this study, the ACR is assessed by the tracer gas technique using carbon dioxide and the concentration decay method. The tracer gas $CO_2$ is injected into the room via two flow regulators, by several injection sets. The $CO_2$ flux and amount is instantaneously supervised and controlled by a manual valve. The injection of tracer gas is stopped when its concentration in the room reaches 3000 ppm while the central ceiling fan stays in operation several minutes. Once the gas is mixed in the room, both the loggia window and the hopper window above the door are opened.
The concentration of tracer gas falls exponentially with the ACR, defined as the volume air inflow rate divided by the space volume, N=q/V (vol/h) (ASHRAE, 2001).

The $CO_2$ concentration in inlet air flow from the loggia window is equal to the outdoor concentration $C_{ext}$ which is roughly constant on the site while the average concentration of $CO_2$ in the room is marked as $\overline{C(t)}$ (ppm):

$$V\frac{d\overline{C(t)}}{dt} + q\,[\overline{C(t)} - C_{ext}] = 0 \qquad (1)$$

When the mixture of $CO_2$ in the room is ensured, the initial value is calculated as average of the sensors $\overline{C(t=0)} = C_{ini}$. The equation can be integrated as:

$$\overline{C(t)} - C_{ext} = (C_{ini} - C_{ext}) \cdot e^{-\frac{q}{V}t} = (C_{ini} - C_{ext}) \cdot e^{-Nt} \qquad (2)$$

In a logarithmic coordinate chart for the average concentration $\overline{C(t)}$ decreases linearly. The ACR is then obtained using a simple linear regression analysis on the logarithmic curve. Because this method is sensitive to the zero drift and tends to overweight the contribution of lowest concentration values, the measure interval is chosen to be between 3000 and 600 ppm in the analysis to avoid the concentration to fall into the range where the relative error of sensors is too significant. The fresh air inflow $q$ *($m^3/s$)* drives the decreasing of $CO_2$ concentration. If there is a high air change, the concentration falls sharply. However, short time of experiment contributes to the instability on measuring the ACR. A test example of cross-ventilation with shutter is presented on Figure 2.

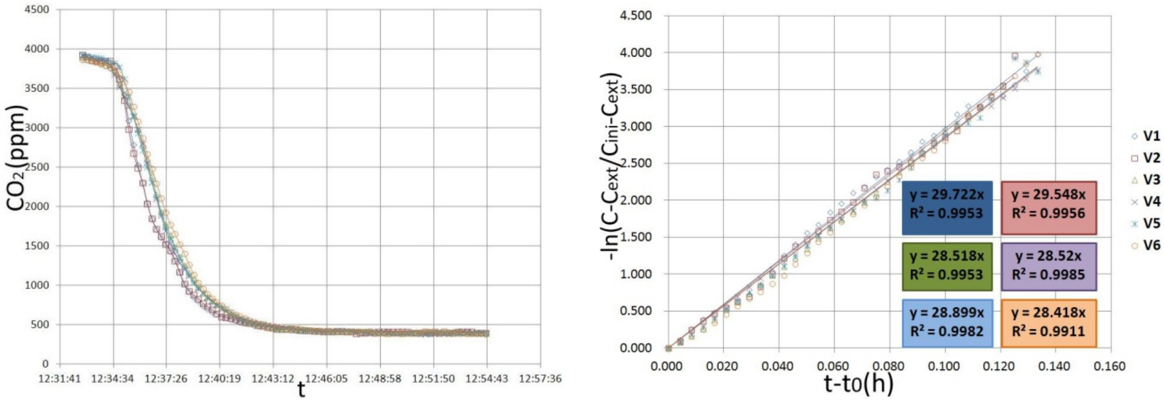



**Figure 2. $CO_2$ concentration decay measure example, test CWS2, sensors Vaisala**

In (Sherman, 1990), the uncertainty related to air change, $\delta N_c$, in regression method can be estimated according to the average decay method.

$$\delta N_c = \frac{1}{\Delta t}\sqrt{\left(\frac{\delta \bar{C}}{\bar{C}}\right)^2 + \left(\frac{\delta C_{ini}}{C_{ini}}\right)^2 + 2\left(\frac{\delta C_{ext}}{C_{ext}}\right)^2} \tag{3}$$

Assuming all the concentrations are measured equally and correctly, the error on sampling is then derived from the measure errors $\frac{\delta N_c}{N_c} \geq 3.3\frac{\delta \bar{C}}{\bar{C}}$.

Another important error source is the mixing imperfection, $\frac{\delta N_m}{N_m}$. As the volume weighting coefficient of each sensor is not easy to determine, the error is found by the deviation from average values of all sensors in one test. Assuming all these uncertainties are independent, the standard deviation is given out by:

$$\sigma^2 = \left(\frac{\delta N_c}{N_c}\right)^2 + \left(\frac{\delta N_m}{N_m}\right)^2 \tag{4}$$

**Location of $CO_2$ sensors**

The location of $CO_2$ sensors is shown in Figure 3. Two types of sensors are used:

- three Telaire Ventostat 800 CO2 sensors of 0-4000 ppm, accuracy 5% of span.
- six Vaisala G70 CO2 sensors of 0-4000 ppm, accuracy 1.5% of span.

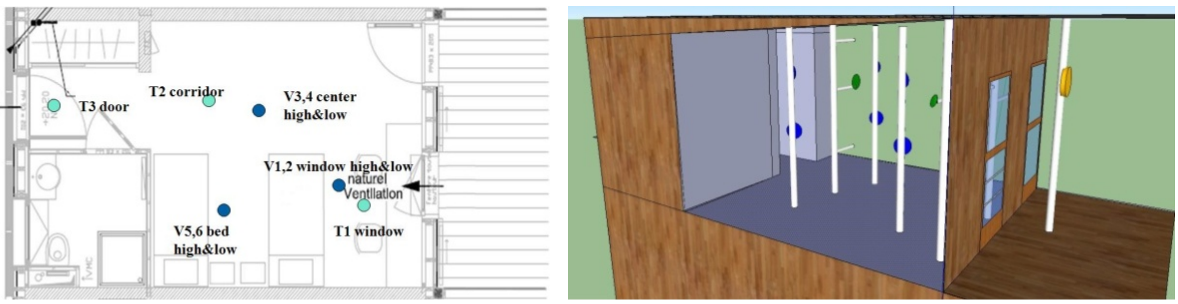



**Figure 3. Location of $CO_2$ sensors ( top and 3D view)**

Thermometers are placed on each wall and in several positions evenly distributed in the room. The average temperature in the room is obtained as the arithmetic mean value of the measured temperature. Three ultrasonic 3D anemometers are set in the loggia, in the center of the room and on the hopper window. Two differential pressure sensors are set on the two facades of the building near the windows. The environmental data are recorded by a meteorological station on the roof.

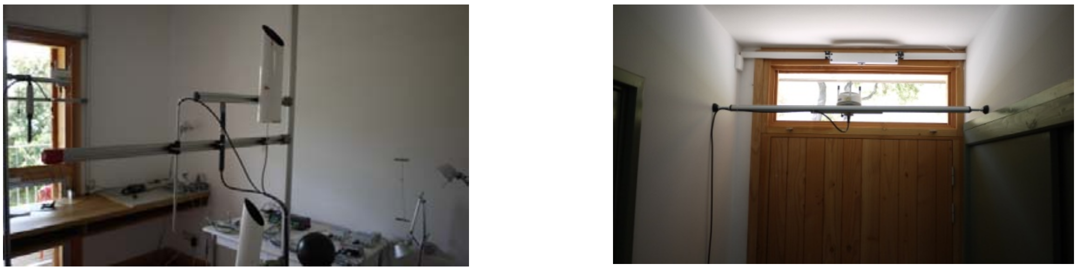
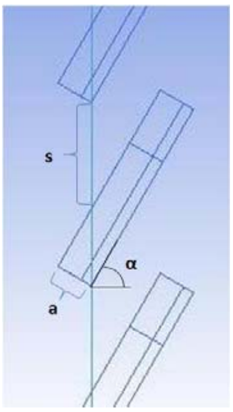


Figure 4. Setting of the sensors

**Ventilation space configuration**
The hotel room is on the second floor, 18 $m^2$ large, 2.68 m high, making a total ventilated volume of 48 $m^3$. A loggia outside is closed by 4 faces. The sealed washroom is not ventilated. The window on the loggia side is 1.08 $m^2$ large and at the opposite of the room, above the entrance door, another window is 0.35 $m^2$ large.

On the loggia side window, a movable blade shutter composed of 12 blades with 60° inclination is installed. The effective surface, *S*, through which the air flows, is defined as the sum of all the narrow passages between the blades (Figure 5). *S* is equal to 0.58 $m^2$, representing 58.5% of the total opening surface.




| | |
|---|---|
| thickness of each blade $a$ | 2.25 cm |
| Inclined angle of blades $\alpha$ | 60° |
| Height of space between blades $s$ | 6.34 cm |
| Effective opening surface $S$ | 0.58 $m^2$ |

Figure 5. Shutter configuration and air flow section

Half of the tests are processed in cross-ventilation with shutter (CWS); half without shutter (CNS). The single-side ventilation cases are introduced as the basis for comparison (SWS and SNS).

## RESULTS AND ANALYSIS

Table 1 sums up the test results, using two methods to calculate the ACR. Method 1 averages the measured concentration by each sensor that is rather stable according to the correlation coefficient of regression curves. On the contrary, method 2 gives out the algebraic average of ACR obtained by the sensors.

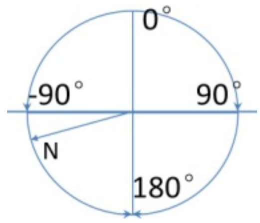
In the cases of cross-ventilation, the wind is too variable during the test period to find two cases identical in the point of view of environmental conditions. The building is located on the seaside and the wind alternates between two wind regimes, typically, coming from sea to mountain in the day and reverse at night. However, in both wind regimes, the ACR is maintained on an acceptable level and is not reduced significantly compared to the cases without shutter at the same experiment time, noted that in this room, the infiltration rate is 0.5±0.1 vol/h and the minimum ACR to keep comfortable indoor air quality is 2 vol/h (CEN, 2007).

Compared to the cross-ventilation cases, the two single-sided ventilation cases picked up are quite similar on environmental conditions. The ACR with shutter (SWS1), $\overline{N}$=1.1 vol/h, equals to 60% of the value without shutter (SNS1), $\overline{N}$=1.8 vol/h.

**Table 1. Measured air change rates**

| | | Environmental conditions | | | Method 1 | | Method 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| *Test* | *Time* | *Wind speed (m/s)* | *Wind direction (°)* | *ΔT (℃ )* | $\overline{N}$ *(vol/h)* | $R^2$ | *N (vol/h)* | $\frac{\delta N_m}{N_m}$ | $\sigma$ |
| CWS1 | 11:40 | 3.43 | 22.3 | 2.0 | 27.9 | 0.996 | 27.9±3.2 | 11.4% | 12.5% |
| CWS2 | 12:20 | 2.97 | 40.8 | 1.8 | 27.1 | 0.992 | 27.2±0.9 | 3.4% | 6.2% |
| CWS3 | 18:55 | 1.51 | 74.3 | 2.1 | 13.6 | 0.995 | 13.9±0.6 | 4.1% | 6.6% |
| CWS4 | 22:15 | 0.98 | 178.5 | 3.6 | 6.7 | 0.986 | 6.6±0.3 | 3.8% | 6.4% |
| CWS5 | 11:20 | 1.93 | 29.9 | 2.1 | 9.6 | 0.977 | 8.9±0.6 | 6.7% | 8.5% |
| CWS6 | 15:15 | 2.29 | 55.2 | 1.7 | 14.1 | 0.993 | 14.4±1.9 | 13.2% | 14.2% |
| CWS7 | 21:21 | 0.74 | -174.1 | 3.4 | 8.4 | 0.988 | 8.1±0.5 | 6.4% | 8.2% |
| CNS1 | 23:00 | 0.63 | -158.2 | 3.7 | 8.3 | 0.985 | 8.2±0.6 | 7.0% | 8.7% |
| CNS2 | 08:08 | 1.98 | 43.9 | 1.6 | 11 | 0.989 | 10.4±1.5 | 14.0% | 14.9% |
| CNS3 | 11:50 | 2.32 | 22.7 | 1.9 | 18.8 | 0.984 | 19.0±1.7 | 9.2% | 10.6% |
| CNS4 | 13:45 | 2.90 | 29.3 | 1.8 | 28.5 | 0.981 | 28.7±2.8 | 9.7% | 11.0% |
| CNS5 | 14:35 | 2.12 | -52.5 | 1.7 | 21.2 | 0.988 | 19.3±2.3 | 12.0% | 13.1% |
| SWS1 | 16:30 | 1.64 | -22.3 | 1.9 | 1.1 | 0.976 | 1.0±0.1 | 11.7% | 12.8% |
| SNS1 | 18:00 | 1.40 | -40.8 | 2.0 | 1.8 | 0.994 | 1.6±0.1 | 7.6% | 9.2% |

*ΔT:* difference between indoor and outdoor temperature.
If the wind comes from the normal direction to the loggia opening, the incident angle is defined to be 0°, the clockwise is positive and anti-clockwise is negative.
The sampling error $\delta N_c$ is calculated using only the most precise sensor (Vaisala).




**Cross-ventilation correlations**

In cross-ventilation, wind is the major driving force of air flow. Nearly all correlations are established on the relation between ACR and dynamic pressure. (Etheridge and Sandberg, 1996) put forth that this ratio can be correlated with differential pressure Δp between two facades, the wind speed U with a discharge coefficient $\Delta C_p$.

$$\Delta C_p = 2\Delta p/\rho U^2 \qquad (5)$$

The calculation formula of crossing air flow is generalized by (Seifert et al., 2005):

$$q = \sqrt{\frac{\Delta C_p}{\sum 1/(A_i^2 C_{di}^2)}} \tag{6}$$

The calculation of $\Delta C_p$ is performed by empirical diagram based on environment obstacle and incident angle. According to experimental results of (Rousseau, 1996), another approach to calculate $\Delta C_p$ is also proposed in function of wind incidence. Both approaches are compared.

**Comparison and discussion**

The experiments are often disturbed by various noises which question the validity to apply the correlations. The value of wind speed in Table 1 is the algebraic mean value of velocity of all registered points in the experiment. As the wind speed is rather instable, it has been found that the use of algebraic mean value of the wind direction for the correlation produce poor results (ACR overestimated by 50% for the cases with shutters and 60% without shutters). Therefore, a new mean value of wind is derived by projecting each wind vector of every time interval in the direction perpendicular and parallel to the opening, then by averaging, and finally by recomposing a new vector. The results are shown in Figure 6. The Rousseau and Mathews correlation, marked RM, is closer to the experimental results than the one of Etheridge and Sandberg, marked ES. However, both overestimate the air flow rates. The ACR is overestimated by 40.3% for CWS, 64.2% for CNS with ES correlation, by 38.8% for CWS, 43.5% for CNS with RM correlation, respectively. The single-sided ventilation correlation developed in (Caciolo et al., 2013) gives also poor results: 0.81 vol/h (-26%) in SWS1 and 3.3 vol/h (83%) in SNS1.

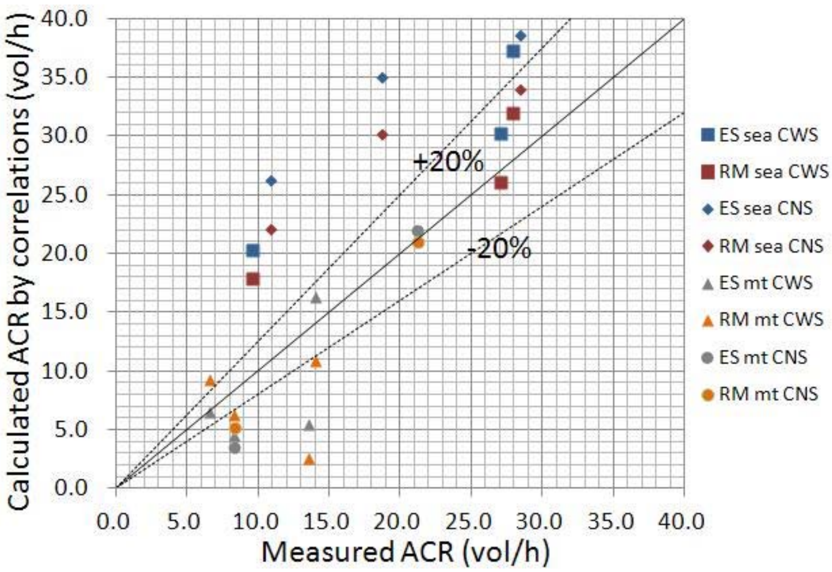



**Figure 6. Comparison between ACR obtained in the tests and from correlations (sea : wind from the sea; mt : wind from the mountain)**

Figure 7 is a projection into an azimuth map of each test (Table 1), represented on a line of same radial direction, with 3 points corresponding to measured and calculated ACR. It is clear that most cases in the daytime with the wind from sea, coming into the large opening, tend to overestimate the ACR. In the evening with the wind from mountain, the practical value is not always overestimated and the difference to theoretical values is lower.

The difference between the experimental results and the correlations could be especially attributed to the configuration of the openings. On one hand, the room has a loggia on the sea side. On the other hand, the effective opening surface is different between the facade and the hopper windows.

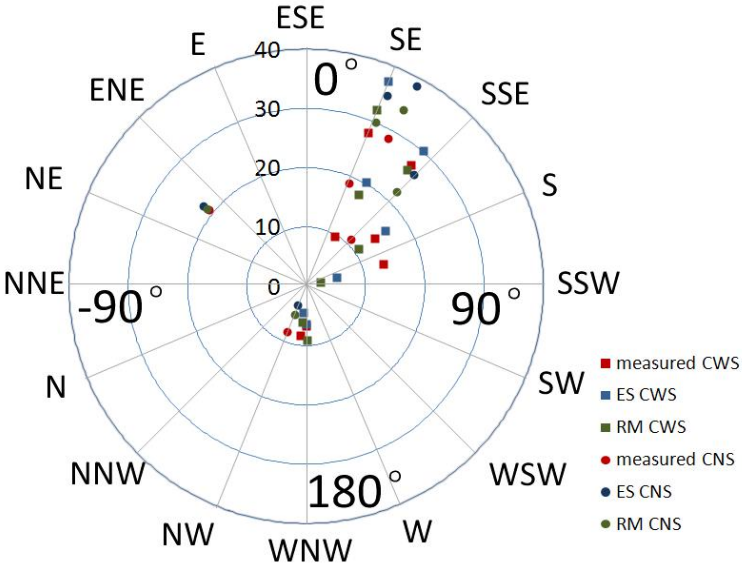



**Figure 7. Measured and calculated ACR N (vol/h) in azimuth map**

To check the influence of the loggia, a CFD simulation has been carried out reproducing the experiment environment conditions. The CFD model specification could be found in (Cui et al., 2013). The CFD demonstrates that the ACR of the room with or without loggia are different. In all windward cases, the loggia reduces by 22% the ACR in average.

CNS4
2.6 m/s
29°
Horizontal cut on
mid-window

with loggia`

without loggia

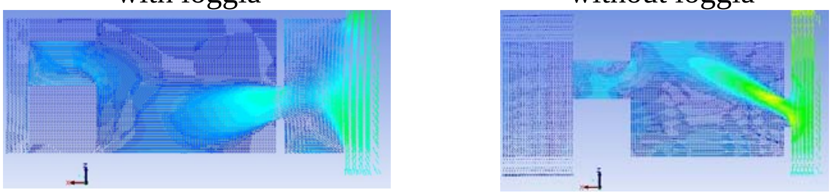


**Figure 8. Wind velocity vector field in CFD simulation (top view)**

The effect of loggia can be observed by the top view in the example presented in Figure 8. When the incident angle increases regarding to the normal direction of opening, the turbulence becomes less negligible. Using the profile of test CNS4, where the incident angle is taken as 29°, the air flow is not stopped by the side of the loggia and normally enters directly the room. But a small turbulence is formed between the window and the loggia edge, changing the direction and reducing the speed of the air flow compared to the case without loggia.

Another reason of the difference between the correlations and the experiments is the large difference of the size between the two openings. In fact, when the shutter is closed, the theoretical results are closer to experiment results because these two open areas are closer in size. In addition, the correlations for air change rate (ES and RM) do not distinguish if the air enters the room by one opening or by another one on the opposite side of building. These results demonstrate the limits of the correlations which require symmetrical building configuration.

## CONCLUSIONS

This work uses tracer gas technique to determine the ventilation rate in a hotel room in Corsica. The experimental data demonstrates that under cross-ventilation situation, the air change rate remains to acceptable value even when a blade shutter is used contrary to single-sided cases. The gas tracer method is a good technique to determine indoor ventilation rate. The measurements errors on gas concentration appear small between different positions and types of sensors in this study.

Though the correlations are simple to apply in practice, there are many limitations in use:

- In case of a room with a loggia, the correlations are not suitable anymore. A CFD study shows that a 4-faces-closed loggia can decrease by 22% the ACR in comparison with a room without loggia in case of a windward condition.
- The two correlations do not well take into account the obstacles in building environment. They don't distinguish the conditions that whether the wind comes from the front side or back side, from the large opening or the small opening. However, the ventilation performances obtained in experiments are not the same.

## ACKNOWLEDGEMENTS

This work is financially supported by French National Research Agency. The experiments were carried out in Institute d'Etudes Scientifique de Cargèse, Corsica, France.

## REFERENCES

ASHRAE (2001) Handbook of Fundamentals, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, (Chapter 26)

Caciolo M, Cui S, Stabat P, Marchio D (2013) Development of a new correlation for single-sided natural ventilation adapted to leeward conditions, *Energy and Buildings*, **60**, 372-382.

CEN (2007) Ventilation for buildings- Calculation methods for the determination of air flow rates in buildings including infiltration, EN 15242

Chao C Y, Wan M P, Law, A K (2004) Ventilation performance measurement using constant concentration dosing strategy, *Building and Environment*, **39**, 1277-1288

Cui S, Gourdon E, Issoglio R, Stabat P, Marchio D, El Mankibi M (2013) How far can 'baffle shutters' attenuate outdoor noise while maintaining acceptable natural ventilation rates? APEC Conference on Low-carbon Towns and Physical Energy Storage

Etheridge D W, Sandberg M (1996) *Building Ventilation: Theory and Measurement.* West Sussex: Wiley.

Hooff T V, Blocken B, Defraeye T, Carmeliet J, van Heijst G J F (2012) PIV measurements and analysis of transitional flow in a reduced-scale model: Ventilation by a free plane jet with Coanda effect, *Building and Environment*, **56**, 301-313

Rousseau P G, Mathews E H (1996) A new integrated design tool for naturally ventilated buildings, *Energy and Buildings*, **23**, 231-236

Seifert J, Li Y, Axley J, Rösler M (2006) Calculation of wind-driven cross ventilation in buildings with large openings, *Wind Engineering*, **94**, 925-947

Sherman M, (1990) Tracer-gas techniques for measuring ventilation in a single zone, *Building and Environment*, **25(4)**, 365-374

Stavrakakis G M, Koukou M K, Vrachopoulos M G, Markatos N C (2008) Natural cross-ventilation in buildings: Building-scale experiments, numerical simulation and thermal comfort evaluation, *Energy and Buildings*, **40,** 1666-1681.