NATURAL VENTILATION DESIGN FOR LOW-RISE BUILDINGS: COMPARISON BETWEEN A NODAL MODEL AND WIND TUNNEL TESTS

François Demouge and Xavier Faure
Centre Scientifique et Technique du Bâtiment
Département Climatologie Aérodynamique Pollution Epuration, Nantes
Université Paris Est

ABSTRACT

The aim of this study is to check the accuracy of a nodal model to predict correctly the flow fields involved inside a building by wind-induced pressure. The model is confronted to experimental tests involving a four-storey dwelling at a reduced scale of 1/20 placed in a wind tunnel facility. Different configurations are tested considering openings of different sizes for outside openings as well as for internal doors and the presence or not of a collective duct connecting the kitchens to the outside at roof level. For each configuration, various wind incidences are studied. Internal pressure coefficient obtained in each room is compared between the experiment and the model. The effects of the variation of the windows discharge coefficient as function of wind incidence is discussed.

INTRODUCTION

Ventilation is an important source of energy consumption since fresh air comes generally from the outside environment. The airflow rate needs to be adjusted so that thermal comfort in summer and the air quality in winter are ensured. These two objectives are to be held while reducing the global energy consumption of the building (French Ministry of Building, Transport and Environment 2010).

Nowadays, there is a growing interest for the use of natural ventilation in temperate and tropical climates. Indeed, in comparison with a classical HVAC system, a natural or hybrid ventilation system appears as an appealing mean to reduce the energy consumption needed to ensure thermal comfort while preserving air quality (Chang, Kato et Chikamoto 2004).

However, an effective design of natural ventilation for a given building can be hard to obtain (Allard 1998) (D. W. Etheridge 2002). Natural ventilation is indeed a complex system composed by some entities with high variability in their characteristics. One has of course to take into account the local climate and to analyze the ratio that can be expected between wind-driven and buoyancy–driven ventilation (Faure et Le Roux 2011). This analyse must be done while including the direct neighbourhood of the building, which means the terrain's topology and the typology of surroundings building (Gandemer 1978). One has also to consider the activity of the occupants, whose comfort criteria can have a strong impact on the operation of the ventilation system, etc. Clearly, the design process relies upon a huge number of iteration steps, which may include in situ testing and a post-construction validation.

Therefore, in the design process of natural ventilation systems, model tests and nodal models appear to be complementary tools. While model tests are necessary to define external pressure coefficients as functions of wind incidence, external architecture and direct neighbourhood, nodal models can give detailed insights on the flow distribution, the thermal comfort and the air quality inside the building. The simplicity of use of nodal models and the low resources required allow one to test easily a large number of configurations (internal distribution, openings size, wall materials, usage scenarios, etc.) (Koffi, Allard et Akoua 2011) (Laverge, et al. 2011). However, there is a need to validate the ability of nodal models to reproduce the various physical phenomena involved (Koffi, Allard et Akoua 2010).

The present paper constitutes a new step towards the validation of a nodal model, MATHIS, developed at CSTB for the design of hybrid ventilation systems and focuses on the ability of the tool in reproducing the interaction between wind-induced pressure and internal architecture of buildings (Demouge, Le Roux et Faure 2011).

In a first step, the main assumptions of the nodal model used are briefly presented. The model allows predicting the internal pressure, temperature and species fields and the openings flow rates depending on internal heat sources, outside wind and temperature conditions.

In a second step, the test apparatus used for confrontation is presented. The apparatus represents a 4 storey building at a reduced length scale of 1/20 and placed in a wind tunnel facility. It is composed of three dwellings of 84 m^2 on three floors and two dwellings of 42 m^2 on one floor. Different configurations were tested considering openings of different sizes for outside openings as well as for internal doors, presence or not of the collective duct and position of the floor composed of two apartments. For each configuration, various wind incidences were studied.

In a third step, numerical and experimental results are compared. This comparison is made for the various configurations tested in terms of pressure field inside the dwelling. The effect of the discharge coefficient of external openings and its evolution with wind incidence is discussed through the example of an optimization using a genetic algorithm.

NUMERICAL MODELLING

The numerical tool MATHIS (***M**odélisation de l'**A**éraulique, de la **T**hermique et de l'**H**ygrométrie **I**nstationnaire**S** d'un bâtiment*) is currently under development at CSTB. The long term aim of the tool is to unify the different nodal models developed along the past years in the different departments of CSTB and dedicated each one to specific studies (mechanical ventilation design, air quality assessment, evaluation of the interaction between heating systems and ventilation systems, fire safety engineering, etc.)..

MATHIS is a nodal model similar to other tools as COMIS (Feustel 1992), CONTAM, (Walton et Dols 2005) or AIRNET (Walton 1989). It is based on the breakdown of the configuration studied into nodes and branches. Each node represents a room or a portion of the ventilation network of a building. Each branch represents the aeraulic components (openings, ducts…) between those volumes. Mass and energy conservations applied in nodes allow one to access to the pressure, temperature and species mass fractions. For the ith node, they can be expressed by the following ordinary differential equations:

$$\frac{dP^i}{dt} = \frac{Cs_P^i/Cs_V^i - 1}{V^i}\left(\dot{E}^i\right) \quad (1)$$

$$\frac{dT^i}{dt} = \frac{1}{\rho^i\left(Cs_P^i - Cs_V^i\right)}\frac{dP^i}{dt} - \frac{T^i}{\rho^i V^i}\left(\dot{m}^i\right) \quad (2)$$

$$\frac{dY_k^i}{dt} = \frac{1}{\rho^i V^i}\left(\dot{m}_k^i \quad - Y_k^i \dot{m}^i\right) \quad (3)$$

Density is deduced using the perfect gas law:

$$\rho^i = \frac{P^i}{T^i\left(Cs_P^i - Cs_V^i\right)} \quad (4)$$

Mechanical energy conservation applied in branches gives the flow rates for each aeraulic component. It takes the form of the generalized Bernoulli equation. For a branch connecting the node i at height z^i to node j at height z^j, it is expressed as follows:

$$\begin{aligned}\frac{L}{A}\frac{d\dot{m}}{dt} = {} & [P^i - \rho^i g z^i + \rho^* g\,(Z_a^i + z^i)] \\ & - \left[P^j - \rho^j g z^j \right. \\ & \left. + \rho^* g\,(Z_a^j + z^j)\right] \\ & + f(\rho^*, \dot{m})\end{aligned} \quad (5)$$

with $f(\rho^*, \dot{m})$ the pressure loss associated to the branch.
For ducts, the pressure loss writes as follows:

$$f(\rho^*, \dot{m}) = -sgn(\dot{m})\frac{\frac{f\,L}{D} + C_0}{2\rho^* A^2}.\dot{m}^2 \quad (6)$$

with f a friction coefficient depending on the rugosity of the duct and Reynolds number.
For branch with small length, we can use the steady state form of equation (5) (which means neglecting the branch inertia). The mass flux through the branch is then deduced as:

$$\dot{m} = sgn(\Delta P).\rho^*.K.\left(\frac{|\Delta P|}{\rho^*}\right)^n \quad (7)$$

with:

$$\begin{aligned}\Delta P = {} & (P^i - \rho^i g z^i) - (P^j - \rho^j g z^j) \\ & + \rho^* g\left[\,(Z_a^i + z^i)\right. \\ & \left. - \,(Z_a^j + z^j)\right]\end{aligned} \quad (8)$$

and:

$$\rho^* = \begin{cases}\rho^i \; if \; \dot{m} > 0 \\ \rho^j \; if \; \dot{m} < 0\end{cases} \quad (9)$$

The numerical algorithm used to solve this set of differential equations is derived from (Woloszin 1999).
Given the aim of the modeling, different optional models can be linked to this aeraulic model (heat diffusion through walls, thermal radiation, combustion, sources and sinks of heat and species, etc.).

TEST APPARATUS

The experiment used for the confrontation of the numerical tool has been done in the framework of studying the potential of wind-driven ventilation for dwellings. We give herein a short description.

The apparatus represents a 4 storey building at a reduced length scale of 1/20. It is composed of three dwellings of 84 m^2 on three floors and two dwellings of 42 m^2 on one floor. Figure 1 and Figure 2 below present the internal architecture of the dwellings.

Each volume communicates with others via the corridor through internal doors and with the outside environment through windows (external openings).

Internal doors and windows are simulated by calibrated holes of 1 cm diameter. The number of holes depends on the configuration tested. These holes have been chosen because of the similarity of their power law with full-scale opening laws and also because of the possibility to simulate numerous porosity ratios.

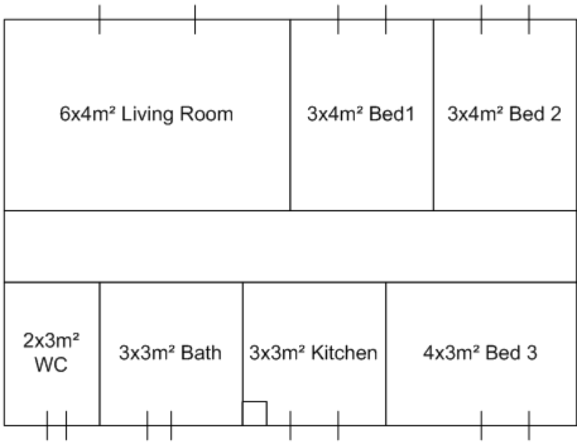

Figure 1: scheme of the internal architecture of the 84 m^2 dwellings

Figure 2: scheme of the internal architecture of the two 42 m^2 dwellings

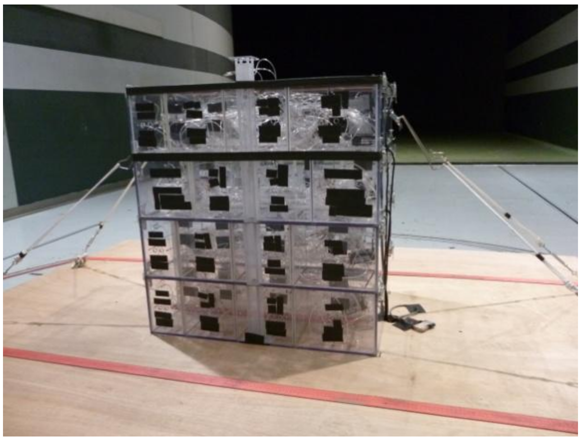

Figure 3: view of the building inside the wind tunnel

The height of the rooms is 3m. The roof is flat. A collective ventilation duct connects all the dwellings at the level of the kitchen. It has a section of 20cmx40cm. The kitchen vent diameter is 20cm. The link between an apartment and the collective duct is done at one storey upper. The last floor is not connected to the collective duct but has its own chimney up to the static extractor on the roof.

Figure 3 presents a view of the model setup inside the wind tunnel. Figure 4 gives a closer view of the collective duct.

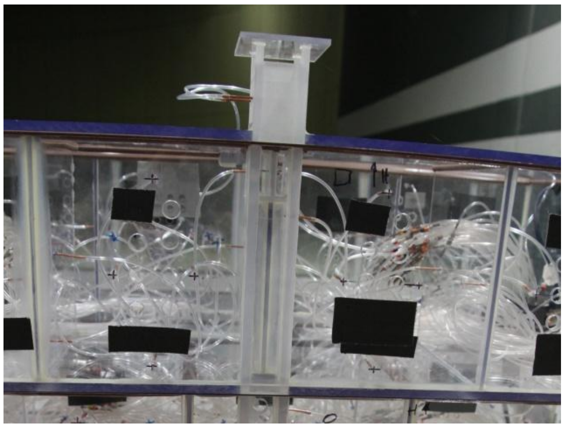

Figure 4: detailed view of the collective duct and static extractor

Different configurations were tested considering openings of different sizes for outside openings as well as for internal doors, presence or not of the collective duct and position of the floor composed of two apartments. 12 configurations have been tested. For each one, four different sizes of windows are set up. Table 2 gives the details of the 6 first configurations. The 6 other configurations are identical except that the floor with the two dwellings switch from the 4th floor to the 3rd floor. For each configuration, wind incidences from 0° to 360° were studied with a step of 20°. This leads to 864 different situations and gives a wide database for the validation of a numerical tool.

Table 1: maximum windows section (m^2)

living	room 1	room 2	room 3	kitchen	bathroom	WC
0.54	0.35	0.35	0.35	0.29	0.29	0.24

Table 2 : details of the configurations studied

conf. N°	Door section (cm2)		windows section (% of maximum section, see table 1)	colllective duct
	kitchen, bathroom and WC	living and rooms		
1	1178	1178	10, 25, 50 and 75	yes
2	1178	1178	10, 25, 50 and 75	no
3	471	471	10, 25, 50 and 75	no
4	471	471	10, 25, 50 and 75	yes
5	235	157	10, 25, 50 and 75	yes
6	235	157	10, 25, 50 and 75	no

The different internal and external pressure coefficients are measured through mean values of four pressure taps positioned around each opening (internal and external). Before calculating the mean value, each pressure taps have been compared to the three others of each element in order to ensure homogeneity or absence of default within taps.

Nearly 250 pressure taps were recorded by PSI sensor at 200 Hz. The wind velocity was recorded with a Pitot tube at 50 cm of the ceiling of the wind tunnel. Several wind speed (10, 15 and 20 m/s) were tested in order to ensure the pressure coefficients (pressure divided by the dynamic pressure) were constant (no Reynolds effect on the pressure field around the building). All the measurements were then done at 20 m/s.

The uncertainty associated to measurement comes from the PSI sensor calibration and the reproducibility of the tests. The PSI sensor calibration error is estimated to be ± 1 Pa. The error of reproducibility is quantified for each wind incidence from the different measurements of external pressure obtained from each test, which are assumed to be independent of the model porosity. The global uncertainty associated to internal pressure coefficients measurement on a two sigma (95%) interval confidence is thus plotted as function of wind incidence on Figure 5 below.

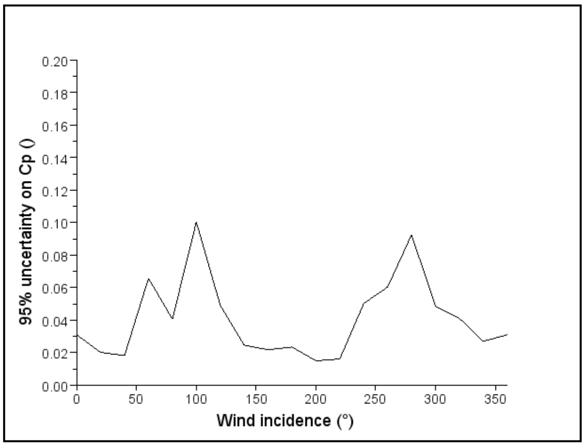

Figure 5: Pressure coefficient measurement uncertainty on a 95% interval confidence plotted as function of wind incidence

COMPARISON BETWEEN EXPERIMENT AND PREDICTION

The model tests are simulated with MATHIS at full scale. The openings are modelled through the orifice equation, based on the Bernoulli's assumption of steady incompressible flow. Thus, the characteristics of the orifice might be included in equation (7) as :

$$\begin{cases} n = 0{,}5 \\ K = C_z . A . 2^n \end{cases} \quad (10)$$

For sharp-edge orifices, high aspect ratios and normal wind incidence, the discharge coefficient C_z is generally taken to 0.6 (Etheridge et Sandberg 1996), which is the value we retain as a first estimate.

External pressure coefficients measured in the wind tunnel are applied to the outside openings of each room. The internal pressure coefficients predicted inside each room are then compared to the measured ones.

Figure 6 presents the correlation obtained between predicted and measured internal pressure coefficient for all the cases, rooms and wind incidence. The coefficient of determination *r2*, defined as the square of the linear correlation coefficient between prediction and experiment, is 0.987. However, it is obvious that the general trend of the numerical model is to give higher C_P than the experiment. Moreover, discrepancy is higher for small values of C_P.

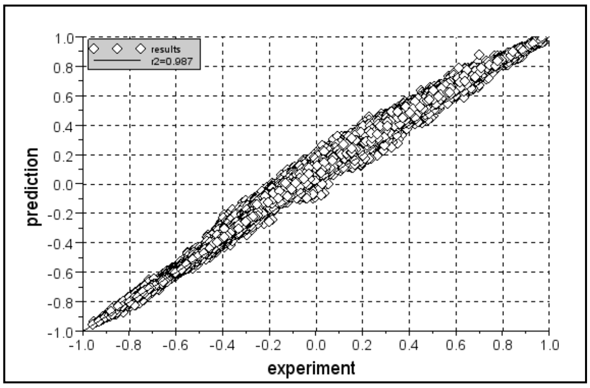

Figure 6: correlation between predicted and measured internal pressure coefficient C_P for all the rooms and configurations with a constant value of C_z=0.6

The observed discrepancy between experiment and prediction can be partly explained by measurement uncertainties, in particular for wind incidences near 90° and 270°. However, the general trend, that is an over prediction of the internal pressure, led us to have a closer look at the discharge coefficient and his effect on the model's results.

For those previous simulations, we used a constant value of the windows discharge coefficient $C_z=0.6$. However, many studies have focused on the discharge coefficient and values that should be given to it depending on wind characteristics (turbulence and incidence), geometrical aspect ratio, wall porosity (Chiu et Etheridge 2007), (Chu, et al. 2009). The discharge coefficient has a great influence on the calculated airflow rate (linear dependency) and using a constant value for every wind incidence could lead to important errors while designing natural ventilation strategies. However, the review made by (Karava, Stathopoulos et Athienetis 2004) indicates that differences have been observed between various study and no general rules exist for choosing the value of the discharge coefficient in a given situation. A previous study at CSTB has also shown a great influence of the relative wind incidence on the discharge coefficient (Faure et Le Roux 2011). From those results we can expect that the interaction between the opening flow and the crosswind flow can be different given the position of the openings on the building and the direction of the opening flow (inflow or outflow), and thus leading to different discharge coefficients.

In the framework of the present study, we tried to see if an optimization of the discharge coefficient C_Z could lead to an enhancement of the global results. We used a SCILAB implemented genetic algorithm. For each wind incidence, the discharge coefficient of the windows is optimized in order to minimize the error between the measured internal pressure and the predicted ones in the rooms of floor 2 for the configuration 2. The discharge coefficient of internal door remains constant and equals 0.6.

Configuration 2 has been chosen because it involves low values of the rooms openings ratios (defined as the ratio between the window section and the door section). Indeed, a sensitivity analysis showed us that it is for low openings ratios that the discharge coefficient has the higher influence on the model results (Faure et Demouge 2013). Moreover, there is no collective duct in this configuration, which allows us to model only the floor 2, thus saving calculation time.

The genetic algorithm is run 50 times for each 18 wind incidence, with a population of 50 individuals and 100 successive generations. For a given wind direction, an individual is defined by the 7 values of the discharge coefficient of the 7 windows.

In order to illustrate the effect of the optimization of the discharge coefficient, Figure 7 presents the evolution of the internal pressure of the living room of floor 2, obtained with a constant C_Z or an optimized one, and compared with the measurement.

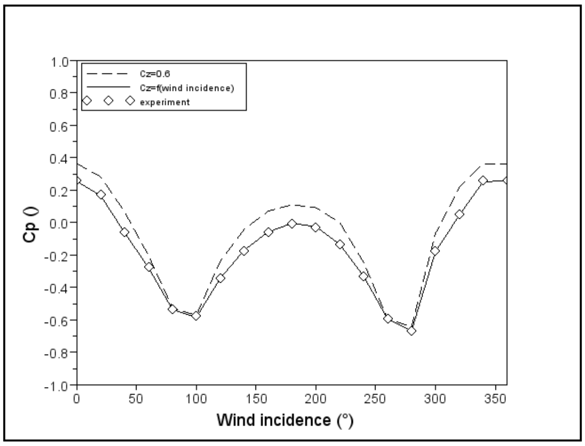

Figure 7 : evolution as function of wind incidence of the internal pressure coefficient Cp in the living room of floor 2 with and without optimisation of Cz

Figure 8 and Figure 9 present the results of 50 runs of the genetic algorithm optimization. For each room and wind incidence, the mean values of C_Z as well as the first and third quartiles are plotted as error bars.

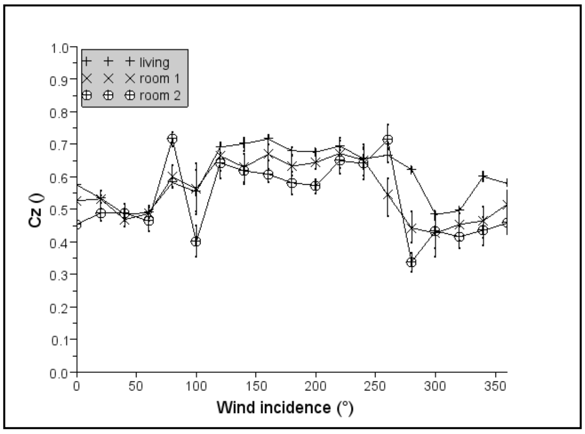

Figure 8: C_Z coefficient as function of wind incidence for openings facing the direction 0° at floor 2

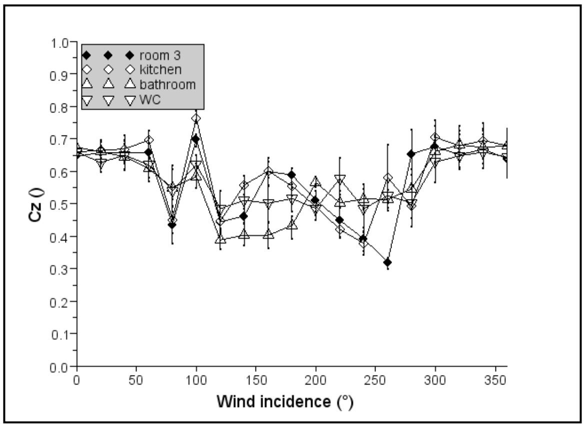

Figure 9: C_Z coefficient as function of wind incidence for openings facing the direction 180° at floor 2

The variations are similar between the different rooms, with $C_Z \approx 0.45$ to 0.55 for relative wind incidence near 0° and $C_Z \approx 0.65$ to 0.75 for relative wind incidence near 180°.

Strong variations of C_Z coefficient are observed for wind incidences near 90° and 270°, which is also where we expect to have the greater measurement uncertainty.

Those C_Z variation laws as function of wind direction have been optimized for the rooms of one floor and one configuration. The simulations of all the configurations have then been done using those laws for all the floors. The results in terms of internal pressure coefficients are presented in Figure 10 below.

The results are obviously better than previously where we used a constant value of $C_z=0.6$. This time, the coefficient of determination *r2* equals *0.996*.

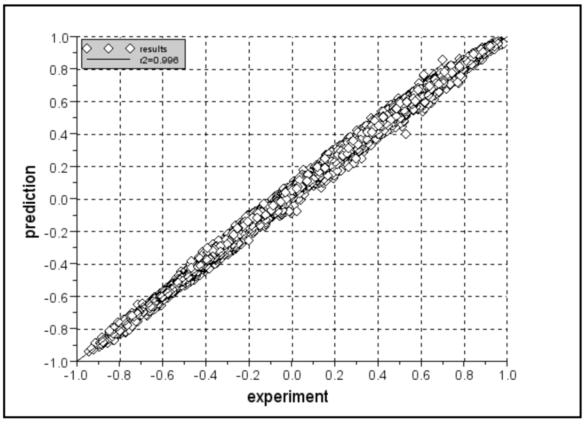

Figure 10: correlation between predicted and measured internal pressure coefficient C_P for all the rooms and configurations with optimized C_Z variation laws

DISCUSSION

The above comparison has shown a good behaviour of the nodal model as compared with the experiment. The use of a constant discharge coefficient for windows leads, from an engineer point of view, to an acceptable margin of error in terms of internal pressure estimation.

However, the observed discrepancy between the experiment and the model can have a non-negligible impact on the predicted ventilation flow rates. In the framework of low energy building and more and more severe requirements in terms of buildings performances, the error made by the model could be unacceptable in a process of global optimization.

In this context, one has to keep in mind the uncertainty attached to the experiment. For example, even though great care has been taken to seal the model, a small porosity can have a significant effect on the measured internal pressures. Moreover, for sharp angles between wind direction and windows orientation, buffeting eddies are expected to occur and thus, the meaning of a mean pressure can be questioned. Clearly, the present work should be pursued with a comparison of the pressures time evolutions and check if the model is able to reproduce the dynamics of the pressure variations due to the turbulence of the wind, in particular for those critical incidences.

The present paper has focused on the effect of the windows discharge coefficient with an optimization using a genetic algorithm. The 50 runs of the genetic algorithm are definitely not sufficient and have been chosen due to calculation time constraints. The number of runs should be increased at least up to 500 in order to have a good representation of the discharge coefficient repartition.

Even if the optimised variation laws of the discharge coefficient as function of wind incidence present some similarities between rooms, the present work should be completed with an evaluation of the effect of the windows elevation on the discharge coefficient behaviour (only the windows of floor 2 have been considered in the optimisation).

Nevertheless, this work does not give a general rule for the choice of the discharge coefficient. It neither gives many clues on the physical phenomena involved. It seems clear from literature that a correction of the classical orifice equation should be applied on external openings in order to take into account the wind characteristics but the way that this correction should be applied is still an active research subject. For example, one could want to apply a correction on the external pressure coefficient rather than on the discharge coefficient. We plan to pursue such kind of investigations as a future work.

Finally, while some ways of improving the model can be considered, one has also to keep in mind that some physical phenomena will never be represented by nodal models, due to their very nature. For example, in a small room, a strong interaction between inflow and outflow dynamics might exists but will not be considered because each openings is modelled independently, whatever the behaviour of the flow inside the room.

CONCLUSION

The present study allows validating the use of a nodal model like MATHIS for the design of wind-driven ventilation systems. In the design process, while wind tunnel tests or thoroughly validated CFD modelling are still needed to obtain the external pressure coefficients to apply on the different façades of a given building, a nodal model can be used to test the effect of various configurations of internal architecture and openings sizes.

This work has also allowed us to propose ways of improving the model, in focusing on the discharge coefficient of external openings and its evolution with wind incidence. However, researches are still needed in order to propose a general correction of the orifice equation able to reproduce correctly the interaction between the flow at the opening and the wind crossflow.

ACKNOWLEDGEMENT

The authors would like to thank Fabrice De Oliveira, research engineer at CSTB, Nantes, for his contribution on the use of genetic algorithms for model fitting to experimental data.

NOMENCLATURE

A	branch section (m^2)
C_P	pressure coefficient
Cs_P	specific heat at constant pressure ($J.kg^{-1}.K^{-1}$)
Cs_V	specific heat at constant volume ($J.kg^{-1}.K^{-1}$)
Cz	discharge coefficient
C_0	singular pressure loss coefficient
D	branch diameter (m)
$\dot{E}$	net heat flux (W)
f	friction coefficient
K	aeraulic resistance ($kgn.m^{-3(n-1)}.Pa^{-n}$)
k	kth specie
L	branch length (m)
$\dot{m}$	net mass flux ($kg.s^{-1}$)
n	flow equation exponent
P	total pressure at the ground of a node (Pa)
R	velocity ratio
T	temperature (K)
U	wind velocity ($m.s^{-1}$)
V	volume (m^3)
W	opening velocity ($m.s^{-1}$)
Y	mass fraction (kg/kg)
z	heigth from the ground (m)
Za	height from reference altitude (m)
ρ	density ($kg.m^{-3}$)
$\rho*$	density of the gas through a branch ($kg.m^{-3}$)

REFERENCES

Allard, F. *Natural Ventilation in Buildings. A Design Handbook*. James & James, 1998.
Chang, H., S. Kato, et T. Chikamoto. «Effects of outdoor air conditions on hybrid air conditioning based on task/ambient strategy with natural and mechanical ventilation in office buildings.» *Building and Environment* 39 (2004): 153-164.
Chiu, Y-H., et D. W. Etheridge. «External flow effects on the discharge coefficients of two types of ventilation opening.» *Journal of Wind Engineering and Industrial Aerodynamics* 95 (2007): 225-252.
Chu, Chia R., Y-H. Chiu, Yan-Jhih Chen, Yu-Wen Wang, et C-P. Chou. «Turbulence effects on the discharge coefficient and mean flow rate of wind-driven cross-ventilation.» *Building and environment* 44 (2009): 2064-2072.
Demouge, F., N. Le Roux, et X. Faure. «Numerical Validation for Wind Driven Ventilation Design.» *32nd AIVC Conference, Brussels*, 2011.
Etheridge, D. W. «Nondimensional methods for natural ventilation design.» *Building and Environment* 37 (2002): 1057-1072.
Etheridge, D., et M. Sandberg. *Building Ventilation. Theory and Measurement*. John Wiley & Sons Inc, 1996.
Faure, X., et F. Demouge. «Sensitivity analysis on the definition of wind driven natural ventialtion potential.» *Building simulation, Chambery, France*, 2013.
Faure, X., et N. Le Roux. «On the potential of wind-driven ventilation for dwellings and low rise buildings.» *Roomvent 2011 - Trondheim, Norway*, 2011.
Feustel, H. E. «The COMIS model.» *Energy and Buildings* 18, n° 2 (1992).
French Ministry of Building, Transport and Environment. *RT 2012*. Édité par CSTB. July 2010. http://www.rt-batiment.fr/batiments-neufs/reglementation-thermique-2012/presentation.html.
Gandemer, J. «Champ de pression moyenne sur les constructions usuelles - Application à la conception des installations de ventilation.» *Cahiers du CSTB*, n° 1492 (Juillet 1978).
Karava, P., T. Stathopoulos, et A.K. Athienetis. «Wind driven flow through openings – A review of discharge coefficients.» *International Journal of Ventilation* 3, n° 3 (2004).
Koffi, J., F. Allard, et J.J. Akoua. «Experimental validation of a numerical multizone airflow and pollutant transfer model.» *CLIMA2010, 10th RHEVA World Congress "Sustainable Energy Use in Buildings*. Antalya, Turkey, 2010.
Koffi, J., F. Allard, et J.-J. Akoua. «Numerical Assessment of the Performance of Ventilation Strategies in a Single-family Building.» *International journal of Ventilation* 9, n° 4 (March 2011): 337-349.
Laverge, J., N. Van Den Bossche, N. Heijmans, et A. Janssens. «Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies.» *Building and Environment* 46 (2011): 1497-1503.
Walton, G. N. «AIRNET - A Computer Program for Building Airflow Network Modeling.» NISTIR 89-4072, NIST, 1989.
Walton, G. N., et W. S. Dols. «CONTAM - User guide and Program Documentation.» NISTIR 7251, NIST, 2005.
Woloszin, M. «Modélisation hygro-thermo-aeraulique des bâtiments multizones - Proposition d'une stratégie de résolution du système couplé.» Thèse de doctorat, Institut National des Sciences Appliquées de Lyon, 1999.