NUMERICAL VALIDATION FOR NATURAL VENTILATION DESIGN

François Demouge[1,*], Nicolas Le Roux[1,2], Xavier Faure[1]

1: Université Paris-Est, CSTB
11 rue Henry Picherit
44300 Nantes, France
**Corresponding author: francois.demouge@cstb.fr*

2: Université de La Rochelle, LEPTIAB
Avenue Michel Crépeau
17042 La Rochelle, France

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 one-storey dwelling of 84 m² at a reduced scale of 1/10 placed in a wind tunnel facility. Different configurations are tested considering openings of different sizes for outside openings as well as for internal doors. For each configuration, various wind incidences are studied. The confrontation shows that the model is able to reproduce the experiment with a relative error of ±20% for situations involving velocity ratios of outside openings greater than 0.2. For lower velocity ratios, higher discrepancy is observed. From an engineering point of view, the results of the model are found acceptable for the evaluation of the potential of wind-driven ventilation of a given building.

KEYWORDS
Wind-driven ventilation, model scale experiment, nodal modelling

INTRODUCTION

Ventilation is an important source of energy consumption since fresh air comes generally from the outside environment. The air mass flow 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 [1].
The use of heat ventilation and air conditioning systems (HVAC) has been widely used until now. It offers the possibility to reach the two first objectives mentioned but it can increase dramatically the energy needs. Concerning dwellings, HVAC coupled with heat recovery system can reduce the energy need in an important manner. Energy efficient building labels as Minergie [2] are good examples of what can be done using HVAC systems. In temperate climates, one can obtain high reduction of energy consumption by considering the potential of natural ventilation for designing hybrid ventilation systems [3]. This potential depends greatly on the site wind velocity and wind direction, but also on the internal architecture and on the areas of internal and outside openings [4].
In the design process of ventilation systems, nodal models can give detailed information on the flow distribution and the air quality inside the building. The simplicity of using nodal models and the low resources required allow one to test easily a large number of configurations (internal distribution, opening sizes, mechanical flow rates, internal

temperatures, usage scenarios, etc.) [5] [6]. However, there is a need to validate the ability of nodal models to reproduce the various physical phenomena involved.
The present paper constitutes a first step towards the validation of the 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. In a first step, the main assumptions of the nodal model used are briefly presented. The model allows to predict the internal pressure, temperature and species fields and 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 model represents a one-storey dwelling of 84 m² composed of 8 internal volumes at a reduced length scale of 1/10 placed in a wind tunnel facility. Different configurations were tested considering openings of different sizes for outside openings as well as for internal doors. 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, openings flow rates and wind driven ventilation potential for a given geographic site.

NUMERICAL MODELLING

The numerical tool MATHIS (***M**odélisation de l'**A**éraulique, de la **T**hermique et de l'**H**ygrométrie **I**n**S**tationnaire d'un bâtiment*) is currently under development at CSTB. The 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 assesment, 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 or CONTAM. It is based on the breackdown 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 i^{th} node, they can be expressed by the following ordinary differential equations :

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

$$\frac{d\rho^i}{dt} = \frac{1}{V^i}\left(\dot{m}_{in}^i - \dot{m}_{out}^i\right) \qquad (2)$$

$$\frac{dY_k^i}{dt} = \frac{1}{\rho^i V^i}\left(\dot{m}_{k_{in}}^i - \dot{m}_{k_{out}}^i\right) \qquad (3)$$

Temperature is deduced using the perfect gaz law :

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

Mechanical energy conservation applied in branches gives the flowrates for each aeraulic component. It takes the form of the steadystate generalized bernoulli equation (which means neglecting the branch inertia). For a branch connecting the node i at height z^i to node j at height z^j, it is expressed as follows:

$$P^i - \rho^i g z^i + \rho^* g\,(Z_a^i + z^i) = P^j - \rho^j g z^j + \rho^* g\,(Z_a^j + z^j) + f(\rho^*, \dot{m}) \qquad (5)$$

with $f(\rho^*, \dot{m})$ the pressure loss associated to the branch. The mass flux through the branch is deduced from (5) as:

$$\dot{m} = sgn(\Delta P).\rho^*.K.\left(\frac{|\Delta P|}{\rho^*}\right)^n \quad (6)$$

with: $$\Delta P = (P^i - \rho^i g z^i) - (P^j - \rho^j g z^j) + \rho^* g\left[(Z_a^i + z^i) - (Z_a^j + z^j)\right] \quad (7)$$

$$\rho^* = \begin{cases} \rho^i \; if \; \dot{m} > 0 \\ \rho^j \; if \; \dot{m} < 0 \end{cases} \quad (8)$$

Given the aim of the modelling, 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 as been done in the framework of studying the potential of wind-driven ventilation for dwellings. We give herein a short description of the apparatus. One will find in ref. [7] full details of the experiment. The apparatus represents a model of a classical one-storey dwelling. Full scale dimensions of the dwelling are 8.5 m large, 12 m long and 3 m high. Figure 1 presents a view of the dwelling in the wind tunnel and a schematic representation of the internal architecture with the functionality of each room. Each room communicates with the corridor through internal doors and with the outside environment through windows (outside openings). 10 different configurations are studied. They are classified as "case n°i - xx%" where i corresponds to different sizes of internal doors and xx to the percentage of the maximum sections of outside opening (see ref. [7] for details of the configurations).

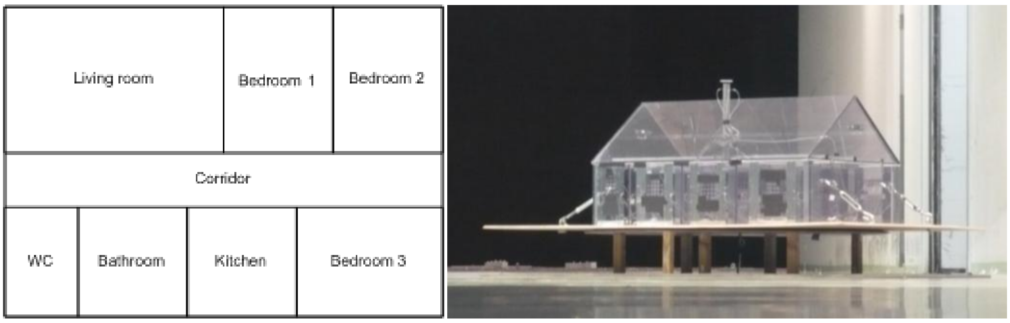

Figure 1: Internal architecture (left) and view of the dwelling in the wind tunnel (right)

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 [8]. Thus, the caracteristics of the orifice might be included in equation (6) as :

$$\begin{cases} n = 0{,}5 \\ K = C_z.A.2^n \end{cases} \quad (9)$$

For sharp-edge orifices, high aspect ratios and normal wind incidence, the discharge coefficient C_z is generally taken to 0.6 [8]. However, as presented in several studies, this parameter can take different values depending mainly on wind incidence and aspect ratios [9][10][11]. The C_z variations of the openings of the scale model have been calibrated with and without wind on a specific bench [7] and are implemented in the numerical model. External pressure coefficients measured in the wind tunnel are applied on the outside openings of each room. The internal pressure coefficients predicted inside each room are then compared to the measured ones. Figure 2 presents an example of results obtained for one of the configuration tested. Figure 3 presents the correlation obtained between predicted and measured internal pressure coefficient for all the cases, rooms and wind incidence. The coefficient of determination r^2, defined as the square of the linear correlation coefficient between prediction and experiment, is close to 0.99. 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.

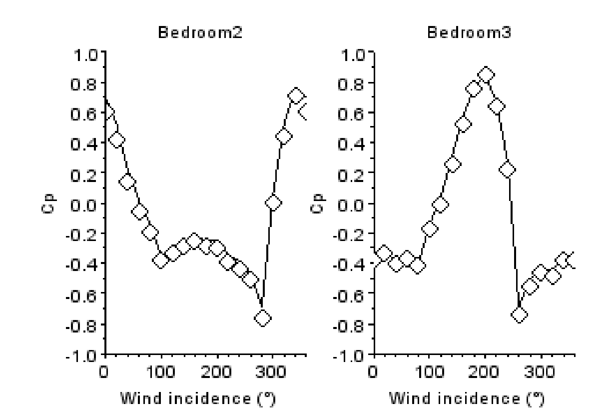

Figure 2: internal pressure coefficients in bedrooms 2 and 3 as function of wind incidence - case n°3 - 50% (◇: experiment; —:prediction)

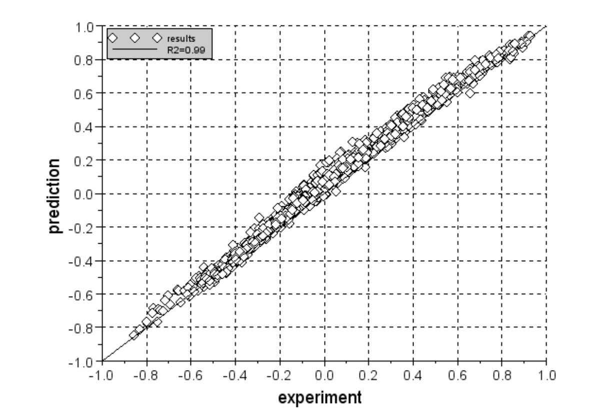

Figure 3: correlation between predicted and measured internal pressure coefficient

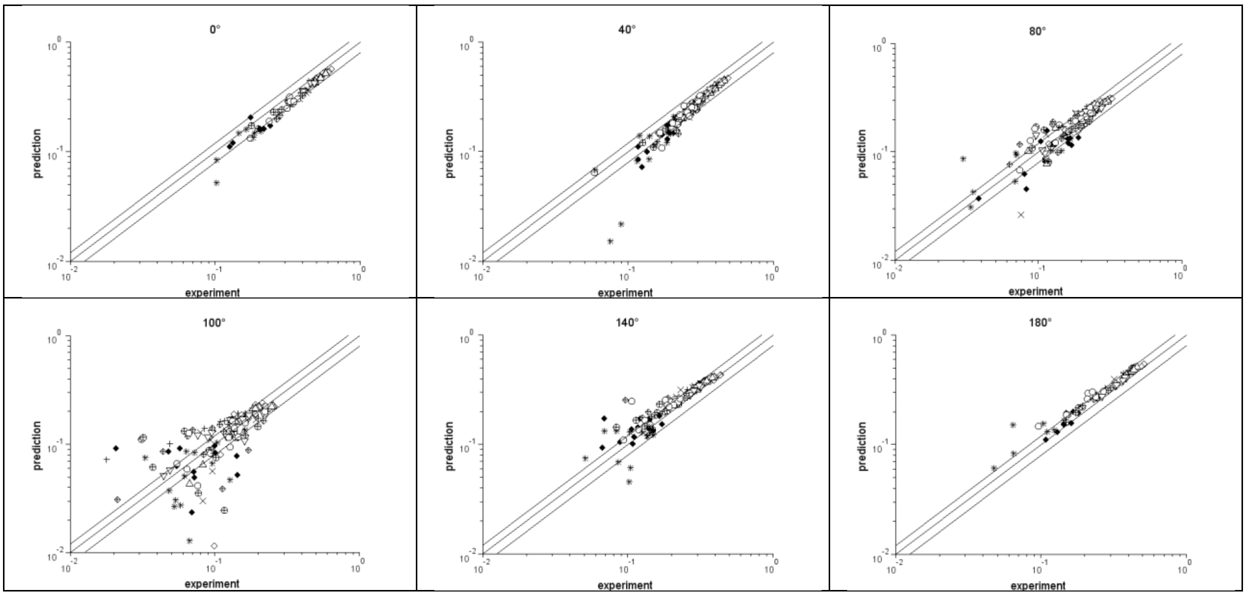

Figure 4: comparison of measured and predicted velocity ratio $R = W/U$ for 6 different relative incidence
○: case n°1 - 10% ; ✳: case n°1 - 25 % ;
+: case n°3 - 10% ; ×: case n°3 - 25 % ; ⊕: case n°3 - 50% ; ◆: case n°3 - 75% ;
Δ : case n°5 - 10% ; ◇: case n°5 - 25% ; ∇: case n°5 - 50% ; ⯐: case n°5 -75%

Figure 4 presents the correlation between predicted and measured velocity ratio R at outside openings defined as $R = W/U$. Results are presented for 6 different relative wind incidences (wind incidence relative to opening orientation). Each set of dots represents a configuration.

The lines represent an error of ±20% relative to the experiment. Those results shows the same general trend for the different relative wind incidences: for *R* greater than 0.2 the numerical results are within 20% from the experiment. For *R* lower than 0.2, high discrepancy is observed between the numerical and the experimental results.
Situations with low velocity ratio *R* are mainly obtained for relative wind incidence near 90°. They are also obtained for configurations with large outside openings and comparatively small internal doors such as for exemple case n°1 - 25% or case n°3 - 75%. On the one hand, this high discrepancy observed for low velocity ratios might be explained partly by measurement uncertainities on mean external pressure coefficient C_P, particularly for wind incidence near 90°. On the other hand, the effect of the differences of geometry between the dwelling and the bench used for openings calibration might also be important on the C_Z variation law for incidences higher than 90°. On this last point, research efforts are currently being done at CSTB with the aim to better understand the effects of wind incidence, Reynolds number orifice, aspect ratio and position of openings on C_Z variations.

Test Case for a real site consideration

The potential of wind driven natural ventilation has then been evaluated for a specific site and orientation using both the experimental results and MATHIS software. The evaluation consists in calculating a satisfaction rate. It is defined as the percentage of time for which the air change rate satisfy the french standard recommendation of $135m^3/h$ within the kitchen for dwellings of more than 5 rooms. Figure 5 and 6 present the wind rose of the considered geographic site (Le Bourget, FRANCE) and the results of the potential of wind driven ventilation for a specific orientation (with the living room facing north) respectively. The residus in Figure 6 are defined as the difference between both approachs on the satisfaction rate.

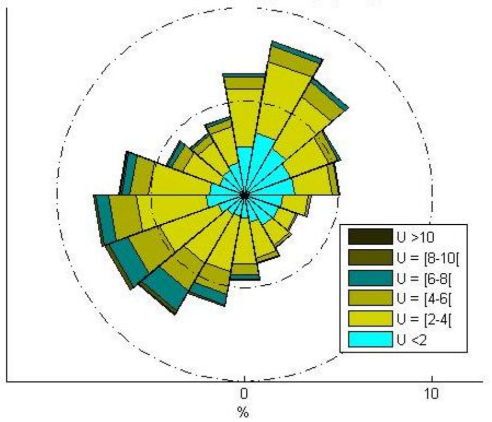

Figure 5: Wind rose of Le Bourget (FRANCE)

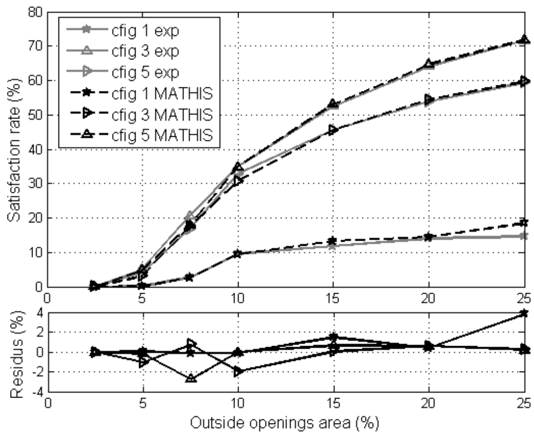

Figure 6: Satisfaction rate for the air change rate in the kitchen depending on the outside openings area

Even if some discrepancies have been previously seen, the global results, considering an engineering point of view, are very good. A maximum of 4% of error is identified on the satisfaction rate between the experiment and MATHIS results.

CONCLUSION

The present study allows to validate 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 modellings 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. Here, the tests involved an isothermal one-storey building only. Others configurations involving several storey and stack effect should be tested in order to complete the validation.

Nomenclature

A	orifice area (m^2)	V	volume (m^3)
C_P	pressure coefficient	W	opening velocity ($m.s^{-1}$)
Cs_P	specific heat at constant pressure ($J.kg^{-1}.K^{-1}$)	Y	mass fraction (kg/kg)
Cs_V	specific heat at constant volume ($J.kg^{-1}.K^{-1}$)	z	heigth from the ground (m)
C_z	discharge coefficient	Z_a	height from reference altitude (m)
$\dot{E}$	net heat flux inside node (W)	ρ	density ($kg.m^{-3}$)
K	aeraulic resistance ($kg^n.m^{-3(n-1)}.Pa^{-n}$)	ρ^*	density of the gas through a branch ($kg.m^{-3}$)
$\dot{m}$	mass flux ($kg.s^{-1}$)		
n	flow equation exponent	*subscripts*	
P	total pressure at the ground of a node (Pa)	*in*	inward
R	velocity ratio	*out*	outward
T	temperature (K)	k	k^{th} specie
U	wind velocity ($m.s^{-1}$)		

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