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SURVEY OF THE EXISTING APPROACHES TO ASSESS AND DESIGN NATURAL VENTILATION AND NEED FOR FURTHER DEVELOPMENTS

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ABSTRACT

In the last years many building designers have turned their attention to natural ventilation, due to the potential benefits in terms of energy consumption related to ventilation and air-conditioning, especially in mild and moderate climates. Consequently, several calculation techniques have been developed to design and predict the performance of natural ventilation.

This article presents a review of the existing approaches to predict natural ventilation performance, including simple empirical models, nodal models (mono-zone and multi-zones), zonal models and CFD models. For each approach, we analyse the physical basis, the main modelling assumptions, the necessary input data and the area of applicability. Thus, the integration of these methodologies in the available simulation programs is examined, with reference to the different phases of the natural ventilation design process and some examples of application are given.

The aim of the review is to identify the main practical limits of existing programs in designing natural ventilation and in predicting its performance and the consequent need for further developments.

LIST OF SYMBOLS

Notation	**Dimensions**	**Meaning**
A	m^2	Area of the opening
A_{cross}	m^2	Cross-sectional area of the room
ACH	1 / h	Air change rate
C_d	-	Discharge coefficient
C_1, C_2, C_3	-	Empirical coefficients
C_p	-	Pressure coefficient
D_{room}	m	Depth of the room
g	m / s^2	Gravity acceleration
H	m	Height of the opening
P	Pa	Pressure
Q	m^3 / h	Volumetric airflow rate
T	°C, K	Temperature
v	m / s	Air velocity
V	m^3	Volume
W	m	Width
Δ	-	Difference
φ	°	Incidence angle of the wind from normal
ρ	kg / m^3	Density

Indexes

B	Buoyancy
in	Indoor
out	Outdoor
rec	Recirculation region
ref	Reference height
w	Wind

INTRODUCTION

Natural ventilation design provides a great challenge to building designers. Indeed, unlike mechanical ventilation, it relies on natural driving forces (i.e. wind and temperature difference) that present a large variability. In consequence natural ventilation is much more difficult in designing (for instance, the size of the openings) and in assessing the comfort level and the energy saving potential than mechanical ventilation.

In this paper, the main models that the designer can use to calculate airflow rates and air speed in natural ventilation are reviewed. Subsequently, the implementation of these models in computer tools are analysed, with respect to the different natural ventilation design phases, and their use is shown and compared by means of examples. Finally, we provide some considerations about possible amelioration of these tools in order to make them more useful in the design practice.

AIRFLOW MODELS

In order to predict natural ventilation performance several airflow models have been developed.

Empirical airflow models

Empirical models consist in correlations derived analytically or empirically to predict ventilation airflow rates of simple opening configurations:

- *single-sided ventilation*

Warren (1985) derives an analytical expression for buoyancy-driven single-sided ventilation:

$$q_B = \frac{1}{3} \cdot A \cdot C_d \cdot \sqrt{\frac{\left|T_{in} - T_{out}\right| \cdot H \cdot g}{\left(T_{in} + T_{out}\right)/2}}$$

and an empirical expression for wind-driven single-sided ventilation based on the results of wind tunnel tests and full-scale experiments in two real buildings:

$$q_w = 0{,}025 \cdot A \cdot v_{w,ref}$$

In case of combination of wind and buoyancy, Warren (1977) proposes to calculate the effect of each parameter separately and then use the largest of them.

Another empirical correlation, which takes into account both wind and buoyancy effects, is derived by Phaff and De Gids (1982) on the basis of 33 measurements on a full-scale building:

$$q_{Bw} = \frac{1}{2} \cdot A \cdot \sqrt{C_1 + \left(C_2 \cdot v_{w,ref}^{\,2}\right) + \left(C_3 \cdot H \cdot \left|T_{in} - T_{out}\right|\right)}$$

Using a similar approach, Larsen (2006) derives a more complex correlation which takes into account also wind direction. The expression is established on the basis of several wind-tunnel tests and 48 full-scale measurements on a real building:

$$q_{Bw} = A \cdot \sqrt{C_1 \cdot \left|C_p\right| \cdot v_{w,ref}^{\,2} + C_2 \cdot H \cdot \Delta T + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{v_{w,ref}^{\,2}}}$$

with

$$\Delta C_{p,opening} =$$

$$9.1894 \cdot 10^{-9} \cdot \varphi^3 - 2.626 \cdot 10^{-6} \cdot \varphi^2 - 0.0002354 \cdot \varphi + 0.113$$

where C_1, C_2 and C_3 are empirical coefficients.

- *Cross ventilation*

CIBSE (1986) proposes two analytical expressions for the calculation of the airflow rate for wind-driven and buoyancy-driven cross ventilation of a simple mono-zone building with two openings on each side:

$$q_w = C_d \cdot A_w \cdot v_w \cdot \left|C_{p,1} - C_{p,2}\right|^{0.5}$$

$$q_B = C_d \cdot A_B \cdot \left(\frac{2 \cdot \left|T_{in} - T_{out}\right| \cdot h_a g}{\left[\left(\mathrm{T_{in}} + T_{out}\right)/2\right]}\right)^{0.5} \qquad \text{where}$$

$$\frac{1}{A_w^{\,2}} = \frac{1}{\left(A_1 + A_2\right)^2} + \frac{1}{\left(A_3 + A_4\right)^2}, \quad \frac{1}{A_B^{\,2}} = \frac{1}{\left(A_1 + A_3\right)^2} + \frac{1}{\left(A_2 + A_4\right)^2}$$

When both wind and buoyancy effects are acting, the actual rate is considered equal to the larger of the rates for the two alternative approaches, taken separately.

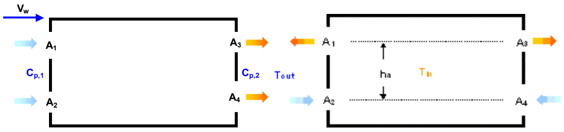

Figure 1 Building geometry and configuration for simple expressions of airflow in cross ventilation

Empirical air velocity models

In order to compute the air velocity in the occupied zone in natural ventilation configurations, few empirical correlations have been developed.

Graça (2003) has developed, using scaling analysis, experimental correlations and CFD analysis, a set of equations providing an approximate prediction of characteristic velocities in cross-ventilated rooms without internal partitions, while knowing the inlet airflow rate.

The maximum velocity in the room, in front of the openings, is calculated as:

$$v_{\max} = \frac{q_{in}}{A_{inlet} \cdot C_d}$$

Therefore, the model calculates the air velocity in two regions of the room, the main jet and the re-circulation regions:

$$v_{jet} = 1.56 \cdot v_{\max} \cdot C_d \cdot \sqrt{\frac{A_{inlet}}{A_{cross}}} \qquad for\ 1/3 < C_L < 11$$

$$v_{rec} = v_{jet} \cdot C_{RJ} \cdot \sqrt{\frac{D_{room}}{A_{inlet}^{\,0.5}}} \qquad C_{RJ} = \begin{cases} 0.191 & for\ 1/3 < C_L < 4 \\ 0.104 & for\ 4 < C_L < 11 \end{cases}$$

with $C_L = \frac{2 L_{room}}{W_{room} - W_{inlet}}$

The model is implemented in EnergyPlus as an optional component.

On the contrary, no empirical models have been developed to predict indoor air velocities in single-sided ventilation.

Nodal models

Nodal (or network) airflow models represent the building as one (single-cell) or more (multi-cells) well-mixed zones, assumed to have a uniform temperature and a pressure varying hydrostatically. Each zone is connected to the other zones and to outside by means of flow paths, representing an incoming or outgoing airflow rate through building elements and characterized by a flow equation in the form $q = f\left(p_{out} - p_{in}\right)$. For large openings, the flow equation is usually the Bernoulli equation: $q = C_d \cdot A \cdot \sqrt{\left(2/\rho\right)\left(p_{out} - p_{in}\right)}$.

The set of equations is closed by writing the continuity equation for each zone, i.e. imposing that incoming and outgoing flow rates are equal. Thus, the unknown pressure for each zone can be calculated.

A single-cell model needs to solve only one equation, as the only unknown is the pressure of the indoor space. Therefore, it is relatively easy to implement an algorithm to solve it, which converges generally quite quickly (Liddament, 1996).

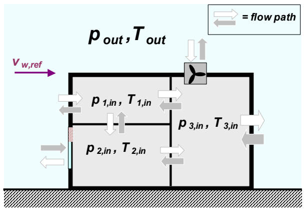

Figure 2 Representation of a nodal model

On the contrary, the resolution of the set of non-linear equations is a challenge of multi-zone network airflow models, especially when coupled with thermal models. The method usually employed to solve the system is the Newton-Raphson method, whose convergence can, in some cases, be very slow or even not assured (Feustel, 1990).

Alternatively, Axley (2001) proposed the use of a method based on loop equations to solve the network. This means that the equations are re-written to form physical closed loops, from inlet to exhausts and back to the inlet again, around which the sum of the pressure changes must equal zero. The loop equation method is implemented in a program called LoopDA (Dols and Emmerich, 2003). One of the advantage of the method is the possibility to use it as "reverse" method to calculate the necessary opening size for a given airflow rate.

Nodal airflow models cannot calculate air speed in rooms, which is an important parameter in the assessment of the thermal comfort.

Furthermore, single-sided ventilation cannot generally be well represented in network models, as it is mainly driven by turbulent fluctuations of wind pressures, neglected in nodal models. To take into account this effect, Daskalaski et al. (1995) propose an empirical correction factor, implemented in one of the most used nodal model (COMIS), which modifies the value of the discharge coefficient as follows:

$$C_d = 0.08 \cdot \left[\frac{g \cdot H^3 \cdot \left| T_{in} - T_{out} \right|}{v_w^2 \cdot D^2 \cdot \left(T_{in} + T_{out} \right) / 2} \right]$$

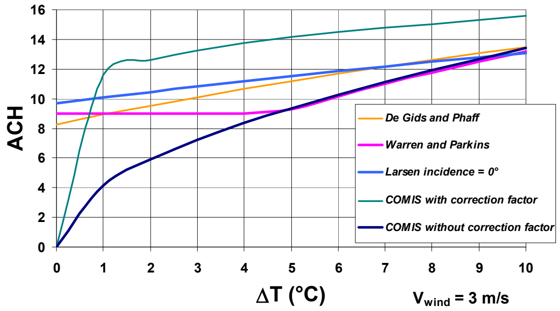

Figure 4 Air change rate prediction of empirical and nodal models

Figure 4 shows the predicted air change rate for single-sided ventilation of a room of dimensions length x depth x height = 2.5m x 5m x 2.8m with an opened windows of dimensions length x height = 1.5m x 1.7m.

It can be noted that model predictions agree reasonably for large temperature differences, where the stack effect is the dominant driving force. However, nodal models with a correction factor over-estimate the air change rate with respect to the other models.

For smaller temperature difference, wind effect becomes dominant, and model predictions show increased differences. In particular, nodal models without correction factors ignore the wind effect, under-estimating the air change rate, while when the Daskalaski correction factor is applied, nodal model over-estimate the air change rate with respect to empirical correlations.

Zonal models

Zonal models are an intermediate approach between nodal models and computational fluid dynamics. In zonal models, each space is further divided into a few macroscopic homogeneous sub-zones which are usually rectangular parallelepiped and in which mass and energy conservation are applied.

The momentum conservation is not directly solved in zonal models in order to reduce considerably computing costs with respect to CFD. Instead, empirical correlations are used to relate the pressure to the mass flow. However, different types of correlations must be used for different zones, i.e. current zones, where momentum forces are weak, and driving flow zones, as jet regions and thermal plumes. Therefore, the user of zonal models must in general specify the airflow patterns associated to each sub-zones. As a consequence, one has to handle special sub-zones during preparation of zonal models, so that in many cases the overhead time in preparing data input for a zonal model may be longer than that for a CFD simulation. Moreover, when driving flows are taken into account, computing time is increased and the equation system is less stable.

These difficulties could also explain the fact that there is no commercial program or software based on the zonal modeling approach (Megri and Haghighat, 2007), limiting the possibility to use this kind of models for design purposes.

Computational Fluid Dynamics (CFD)

CFD programs solve numerically the Navier-Stokes equations, i.e. mass, momentum and energy conservation, in a fluid domain, providing detailed information about pressure, speed and temperature at each point.

CFD has been successfully applied to different situations in natural ventilation design:

- Calculation of wind pressure coefficients;
- Determination of air velocity and temperature distribution in naturally ventilated spaces;

- Calculation of airflow paths around and inside naturally ventilated buildings.

When dealing with CFD simulation of natural ventilation, the designer should take many modeling decision:

- *Domain extension*: typically, CFD simulation of natural ventilation requires a coupled simulation of the interior and of the exterior of the building. However, it is possible, in some situations, to divide the two domains and to perform separate calculations (Cook et al., 2003).
- *Mesh topology and density*: the choice of the mesh scheme plays a key role in the success of a CFD simulation. Use of both structured (Straw, 2000) and unstructured mesh (Yang, 2006) is possible. Typically, the mesh must be fine enough to capture the main features of the flow in some key zone (near openings and solid boundaries), but coarse enough to limit the total number of control volumes.
- *Turbulence model*: flow around and inside buildings is turbulent. Turbulence is usually taken into account by means of Reynold Averaged models (RANS), i.e. k-ε or k-ω models. Standard k-ε model fails to predict correctly external flow around buildings (Franke et al., 2004), thus use of RNG and realizable k-ε models is recommended. In principle, unsteady turbulence models (Large Eddy Simulation, LES) give the best results for natural ventilation, especially when unsteady turbulent effects are likely to be important (Jiang and Chen, 2001). However, the large amount of computational resources needed for this type of simulation and the heavy mesh requirements makes the use of LES not reliable in practical situations. To overcome this limitation, hybrid RANS/LES

Table 1: Features of available airflow models

	Inputs	Configurations	Available models	Outputs
Empirical models (airflow rate)	⇒ Outdoor and indoor temperature ⇒ Wind speed and direction (Cp) ⇒ Height, Cd and area of each external opening	⇒ Single-sided ventilation ⇒ Cross ventilation	⇒ Single-sided ventilation: o Warren (1985) o Phaff & De Gids (1982) o Larsen (2006) ⇒ Cross ventilation: o CIBSE (1986)	⇒ Airflow rates
Empirical models (indoor air velocity)	⇒ Room and opening geometry ⇒ Airflow rate ⇒ Indoor and outdoor temperature ⇒ Position of occupied zones	⇒ Cross ventilated room with two openings in opposite sides and no obstructions	⇒ Graça (2003)	⇒ Indoor air speed in the occupied zone
Mono-zone nodal models	⇒ Outdoor and indoor temperature ⇒ Wind speed and direction (Cp) ⇒ Height, Cd and area of each external opening	⇒ Cross ventilation without obstructions	⇒ AIDA (Liddament, 1996) ⇒ European standard EN 15242:2006 ⇒ NatVent, NiteCool (Svensson & Aggerholm, 1998)	⇒ Airflow rates and internal pressure
Multi-zone nodal models	⇒ Outdoor and indoor temperatures ⇒ Wind speed and direction (Cp) ⇒ Height, Cd, area and zone of each external opening ⇒ Height, Cd, area and zones connected of each internal partition	⇒ Cross ventilation with obstructions ⇒ Single-sided ventilation (COMIS only)	⇒ COMIS (Feustel, 2001) ⇒ CONTAM (Walton & Dols, 2005) ⇒ LoopDA (Dols and Emmerich, 2003)	⇒ Airflow rates and internal pressure of each zone
Zonal models	⇒ Geometrical space description ⇒ Definition of current zones, jet zones and plume zones ⇒ Boundary conditions ⇒ Distribution of heat sources ⇒ Indoor and outdoor temperatures	⇒ Virtually any kind of configuration, if boundary conditions are properly set	⇒ POMA (Haghigat et al., 2001) (*research tool*)	⇒ For each sub-zone: o Air speed o Pressure o Temperature
CFD models	⇒ Fine geometrical description of the domain ⇒ Pressure or flow rate at the boundaries ⇒ Distribution of heat sources ⇒ Indoor and outdoor temperatures	⇒ Virtually any kind of configuration, if boundary conditions are properly set	⇒ Fluent ⇒ CFX ⇒ AirPak ⇒ MicroFlo	⇒ Indoor domain: o air velocity, temperature ⇒ Outdoor domain: o C_P coefficients ⇒ Coupled indoor and outdoor: o Airflow rates, indoor air motion

approaches have been developed but their use is still subject to research (Wright and Hargreaves, 2006).

- *Boundary conditions*: For the analysis of the flow around a building, the speed and the turbulence profile of the approaching wind must be specified. Moreover, the terrain and the lateral and top boundaries should be set properly in order to avoid altering this profile (Franke et al., 2004). When the computational domain is limited to indoor, velocity (Graça, 2003) or pressure (Cook et al., 2003) boundary conditions can be prescribed. Thermal boundary conditions should also be carefully set in order to reproduce thermal sources and wall temperatures.

Despite the difficulties inherent the choice of all these parameters, CFD is becoming more and more popular due to the increase in computer capacity and the development of many user-friendly and graphical interfaces, commercially available, including the popular Fluent and CFX-Ansys. Moreover, some CFD programs have been specifically developed for ventilation analysis, including AIRPACK, add-on of Fluent, and the CFD solver MicroFlo, part of the simulation tool IES Virtual Environment <VE>.

Table 1 summarizes the main features of all the reviewed models.

NATURAL VENTILATION DESIGN IN PRACTICE

In short, three main phases of the design of a building can be defined (Axley, 2002):

1. *Predesign analysis and conceptual design*: the building geometry and thermal characteristics are still roughed in. In this phase, the outline and the general characteristics of the ventilation system are defined.
2. *Design developement*: the building geometry and characteristics are defined in detail. Consequently, the designer can determine a design airflow rate and the corresponding design conditions (e.g. temperature, wind speed and direction, etc.) and size the openings. The details of the control strategy are also defined.
3. *Performance evaluation*: assessement of the performance (in terms of energy consumption and comfort) of the building with the natural ventilation system in conditions other than design ones, generally on an annual basis. In this phase, final tuning of opening size and of operational strategy is achieved. Moreover, the overall design is verified with respect to the initial objectives of energy consumption and comfort.

Each one of these three phases needs adequate tools to support the decision-making process.

Pre-design analysis and conceptual design

Some key decisions, decisive for the success of natural ventilation, are taken in the very first stage of the design process, when details about the building envelope and its characteristics are still not available.

Basic choices concern, for example:

- *Natural ventilation configuration*:
  - single-sided ventilation;
  - wind-driven cross ventilation;
  - stack-driven cross ventilation.
- *Natural ventilation strategy:*
  - Daytime and night ventilation;
  - Night ventilation only.
- *Use of assisting mechanical ventilation and of active cooling.*

These choices depend on many factors, including:

- Building location, shape and layout (cellular or open space offices, depth to height ratio);
- Possibility to insert specific components for ventilation (chimneys, stacks) or to use available architectural elements (operable windows, atria) for ventilation purposes
- Size and type of glazed surface;
- Internal gains;
- Comfort expectations of occupants.

In this phase, the most useful tools are general design guidelines and handbooks, as Allard (1996) and CIBSE (2005). Etheridge (2001) proposes the use of graphs and non-dimensional parameters based on empirical correlations.

However, a quantitative analysis tool could give interesting indications of the potential of the different options, in terms of energy consumption and overheating risks, taking into account some of the factors and constraints mentioned above.

The ideal tool would couple a simplified thermal model, with few selected inputs, and empirical correlations for single-sided or cross ventilation. The user should be able to preclude some options (e.g. daytime ventilation in polluted environments, stack ventilation if prohibited by fire regulation) and to perform easily parametrical analysis. The outputs of the model should be given in terms of potential of each natural ventilation strategy, with a rough evaluation of the energy consumption and of the overheating risk corresponding to different opening areas. Emphasis should be given to the possibility for the user to understand quickly the effect of the building parameters on the potential of the different natural ventilation strategies. Moreover, the result presentation should be attractive, as the tool should also be used as instrument of communication with the architect and the contracting owner.

An interesting program in this direction was developed in the frame of the European project NatVent (Svensson and Aggerholm, 1998). A mono-zone nodal model is integrated to a mono-zone heat balance model and calculates the indoor temperature and ventilation flow rate during the summer season, the winter season or during the whole year. The program disposes of a user-friendly interface and seems easy to use, but it has not been maintained after its first release, and it is not very robust and bugs often. The choice of weather data is also very limited.

Building Energy Simulation (BES) programs have also the potential to satisfy some of the requirements described above. For exemple, Caciolo et al. (2008) present a simplified methodology to estimate the potential of daytime ventilation, coupling a BES program to empirical airflow models. The BES program calculates the cooling demand of the building without natural ventilation. Thus, the airflow rate necessary to avoid the cooling load in each zone is calculated as:

$$q = \frac{Q_{cooling}}{\rho \cdot c_P \cdot \Delta T}$$

and the opening area is calculated based on empirical correlations. The result is given in terms of opening area, expressed as ratio of façade area, versus the outdoor temperature for which natural ventilation is able to avoid overheating without the need of active cooling (figure 5).

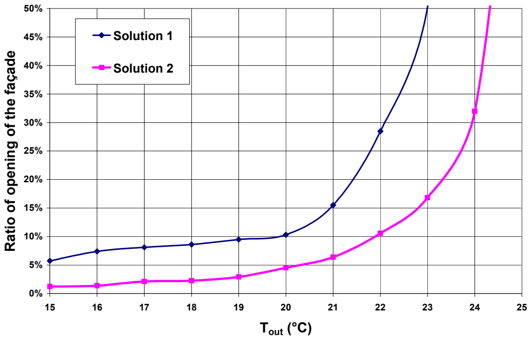

Figure 5 Example of necessary ratio of opening on the façade to avoid overheating for two buildings

Design development

Once the building layout, its thermal characteristics and the overall ventilation strategy have been defined more precisely, the ventilation system should be designed in more detail. In practice, this means sizing the openings and choosing their type.

At first the design airflow rate should be defined. Two airflow rates are generally specified: a "winter" airflow rate, for control of indoor air quality, and a "comfort" airflow rate, for control of overheating, which is usually much higher. The design procedure and the possibility to use existing tools are different for the two cases.

For winter ventilation design the airflow can be considered uncoupled from the thermal behavior of the building. The design airflow rate corresponds to the minimum fresh airflow rate required by national regulations or standards and the indoor temperature can be assumed constant and equal to the heating set-point temperature. Pessimistic outdoor design conditions (i.e. no wind and low temperature difference) can be used to size the opening. Thus, the opening area can be calculated based on rules of thumb, empirical correlations or stand-alone airflow modeling programs, e.g. LoopDA. The control strategy can be defined by means of the same tools in order to maintain a reasonably constant airflow rate, reducing the opening area.

On the other hand, for "comfort" natural ventilation, intended to avoid overheating of the building, sizing procedure is actually different. Indeed, the size of the openings for comfort ventilation should be as large as possible to allow the introduction of the maximum amount of outdoor air. However, two factors limit the maximum value:

- The maximum structural opening area available on the façade, due to the architecture of the building and to safety reasons (e.g. one could want to limit the opening area during the day to avoid accidents or during the night to avoid intrusions);
- The maximum opening area to avoid excessive air speeds in the occupied zone, in order to avoid unpleasant draft perception and undesired effect as paper being blown off office desks.

The opening area should be then the smaller of the two areas.

However, the assessment of the indoor airspeed depends strongly on the typology of the opening and needs generally to recur to CFD. An alternative and simpler method consists in using empirical correlations as the one of Graça (2003). Unfortunately, the correlation has been established only for a very simple configuration (two openings on two opposite sides) and does not take into account the opening type and configuration.

Further experimental and simulation analysis are necessary to develop new correlations for other configurations. In particular, the authors are investigating the possibility of establishing simple correlations for common single-sided and cross ventilation configurations and opening types, by using CFD analysis.

Performance evaluation

To analyse the annual energy and comfort performance of a building it is common practice to use Building Energy Simulation (BES) programs.

Many of the most used BES programs intend to simulate mechanically ventilated buildings, implementing basic infiltration models and imposed ventilation airflow rate. However, an increasing number of BES programs are integrated or can be coupled with multi-zone airflow models in order to take into account natural ventilation.

Beside that, no BES program implements explicitly empirical models for single-sided ventilation. A partial exception is represented by TRNSYS, where, thanks to its modular structure and the possibility to insert equations, the user can easily add empirical models. Moreover, TRNSYS can be coupled with the airflow multi-zone program COMIS, which implements the empirical model of Dascalaki et al. (2005).

Thus, TRNSYS has been used to compare the results of coupling different models of single-sided ventilation with a BES program (TRNSYS Type 56).

Figure 7 shows the peak operative temperatures calculated for an office room exposed to South in Nice (France), with thermal characteristics corresponding to the French Thermal Regulation and 17 W/m^2 of internal gains. The office has dimensions length x depth x height = 2.5m x 5m x 2.8m with an operable vertical sliding windows of dimensions length x height = 1.8m x 1.7m. The maximum opening area is set to half of the structural area and the control strategy is of type on/off.

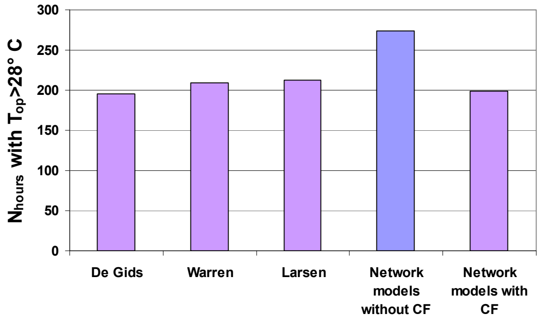

Figure 7 Peak operative temperature for single-sided ventilation with different empirical models

It can be noted that results are not very sensitive to the empirical model used. On the contrary, as expected, using airflow models without any correction factor under-estimates the potential of single-sided ventilation, due to the fact that they do not consider wind effect.

To give a more detailed assessment of thermal comfort, air speed should be included in the calculation of the operative temperature or of a similar comfort index (PMV, PPD, etc…). For the examined case, for example, even if operative temperature is higher than 28°C for more than 200 working hours per year, the moderate air movement created by single-sided natural ventilation is expected to make this temperature more acceptable. In principle, this could be quantified by coupling the thermal model to a CFD model. However, running CFD on an annual basis is a very time-consuming and laborious task, which is probably not justified for this aim. A better solution would consist in using empirical correlations, but, as said, they are not available for single-sided ventilation.

The utility of such a correlation is better illustrated by introducing a simple case of cross ventilation, where the correlation of Graça can be used. The case consists in an open plan office of dimensions length x width x height = 5m x 12m x 2.8m with two sliding openings, one external exposed to south and the other communicating with a stack 10m height. The maximum opening area of the window in the façade corresponds to 25% of the façade, while the top opening area is taken to 2 m$^{2.}$ The openings are opened and closed based on the outdoor and indoor temperature with an on/off regulation strategy. A mechanical exhaust ventilation system assures the minimum fresh airflow rate when openings are closed. The office is situated in Nice, has 17 W/m^2 of internal gains and no air-conditioning. It is supposed that the opening at the top of the stack can be oriented to maintain a constant negative wind pressure coefficient difference of 0.3.

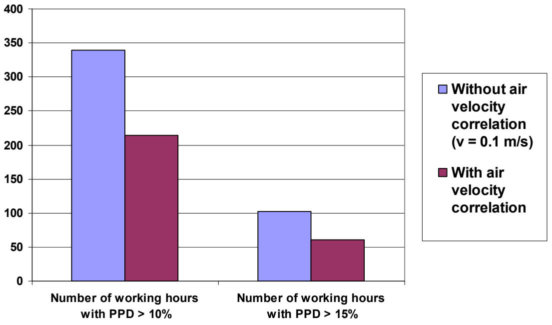

Figure 8 Number of discomfort hours for a sample cross-ventilated office room when airspeed is taken into account or not

Figure 8 shows the predicted number of working hours during which the index PPD, as defined in the European standard EN 7730, exceeds 10 and 15 %. The first calculation is carried out considering a constant air speed of 0.1 m/s, while the second one with the air velocity calculated according to Graça.

It can be noted that when air speed is taken into account, the number of uncomfortable hours is almost half than if air speed were not considered.

CONCLUSION

In this paper, the main models to calculate airflow rates and air speed in natural ventilation have been reviewed. The implementation of these models in available computer tools has also been analysed with respect to the main design phases.

The review has shown that a considerable number of models have been developed for the analysis of natural ventilation. However, there are still areas in which few or no models are available. This is the case of the assessment of air speed in many natural ventilation configurations, for which no empirical or semi-empirical models are available. Therefore, in order to avoid recurring to CFD, particularly demanding in terms of time, computing resources and user knowledge, further simplified models should be developed and validated.

Furthermore, we have examined the functionality of BES programs in simulating naturally ventilated buildings on an annual basis. The most advanced BES programs implement a multi-zone airflow network model coupled to a multi-zone heat transfer model. This approach can today be considered the state-of-the-art of coupled thermal and airflow building simulation. However, it has been shown that it is recommended to introduce in network models an empirical correlation to take into account wind effect in single-sided ventilation. With this correction, the predictions of network models and of the existing empirical models are similar.

Finally, the incidence of the effect of the air speed on thermal comfort assessment in a sample cross-ventilated space has been evaluated. The calculation shows that, for non-air-conditioned spaces, it is important to consider the effect of the air speed on thermal comfort.

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