Int. J. of Solar Energy, 1997, Vol. 19, pp. 81–119
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NATURAL VENTILATION RESEARCH ACTIVITIES UNDERTAKEN IN THE FRAMEWORK OF PASCOOL

K. LIMAM[a,*], F. ALLARD[a] and E. DASCALAKI[b]

[a] *LEPTAB, Universite de La Rochelle, Departement Genie Civil et Mechanique, Avenue Marrillac F-17042 La Rochelle, Cedex 9, France;*
[b] *GR-BES, University of Athens, Department of Physics, Division of Applied Physics, Laboratory of Meteorology University Campus, Build. PHYS-V, Athens, GR 15784 Greece*

(Received in final form 4 July 1996)

Natural Ventilation is a widely used passive cooling technique in the countries of southern Europe. Numerous studies have been devoted to the analysis of the physical phenomena related to natural ventilation. These phenomena are very complex and our degree of understanding them often leaves a lot to be desired. Research on this topic within the framework of PASCOOL included experimental and modeling work aiming to fill existing gaps in our knowledge of indoor air conditions in naturally ventilated buildings. An extensive experimental program was carried out in full scale buildings and test cell facilities during the summer period in Greece, Belgium, Spain, Switzerland and Portugal. Existing models were validated and new ones were proposed. This paper gives a brief description of the experimental work and summarizes the results from the data analysis and model development within PASCOOL.

Keywords: Natural ventilation; Passive cooling

1 INTRODUCTION

As revealed by the last ZEPHYR competition [1], natural ventilation is the first design strategy used by architects or designers to reduce building cooling loads and improve indoor comfort in Mediterranean countries where air conditioning systems do not represent a realistic alternative.

* Corresponding author.

Natural ventilation through large openings is distinguished in cross and single sided ventilation. Cross ventilation is strongly influenced by the wind characteristics and the flow depends directly on the pressure differences at the multiple openings. The difficulty in predicting the flow in cross ventilation configurations is mainly due to the uncertainty in the pressure coefficients at the openings. When all openings are in one wall only or there is a single opening (single sided ventilation), thermal buoyancy and wind-induced pressures are the driving forces of ventilation. Prediction of the ventilation rates for design assessment purposes is a complex problem and various methods and models have been proposed. However, very few experimental studies are available and the validation of existing models is very limited.

The research effort in PASCOOL included both experimental and modeling activities in the field of natural ventilation. Experimental work on single sided and cross ventilation was carried out in full scale buildings and test cell facilities. Difficulties in experimental methods were reported. Data from the experiments were used in order to validate modeling approaches. New models were developed and validated using experimental data. In the following sections the research work undertaken within the framework of PASCOOL in single sided and cross ventilation is presented..

2 SINGLE SIDED NATURAL VENTILATION STUDIES IN PASCOOL

2.1 Modeling Approaches

Previous studies on single sided natural ventilation configurations can be classified in four major groups: (a) simplified empirical models, (b) network prediction models, (c) pulsation models and (d) Computational Fluid Dynamics (CFD) modeling.

2.1.1 Simplified Empirical Models

Simplified empirical models, offer general correlations to calculate the air flow. These expressions combining the air flow with the temperature difference, wind velocity and possibly a fluctuating term are deduced either from theoretical or from specific experimental data and cannot be considered of general validity; therefore, they should be used within the limits of their applicability.

The British Standards Method [2], proposes formulae for the calculation of the air flow in single sided and cross ventilation configurations. The method assumes two-dimensional flow through a building and ignores all internal partitions. The proposed formulae for single sided ventilation are:

(a) Ventilation due to wind:

$$Q = 0.025 \cdot A \cdot V \quad (\text{m}^3/\text{s}), \tag{1}$$

where A is the opening surface and V is the wind velocity and Q is the volumetric air flow rate.

(b) Due to temperature difference with two openings having a surface equal to A_1 and A_2 respectively:

$$Q = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}}\right]\sqrt{\frac{\Delta T g H_1}{\overline{T}}} \quad (\text{m}^3/\text{s}), \tag{2}$$

where C_d is the discharge coefficient and $\varepsilon = A_1/A_2$. Also ΔT is the temperature difference between indoor and outdoor, H is the vertical distance between the two openings and $\overline{T}$ is the mean indoor–outdoor temperature.

(c) Due to temperature difference with one opening:

$$Q = C_d \frac{A}{3}\sqrt{\frac{\Delta T g H}{\overline{T}}} \quad (\text{m}^3/\text{s}), \tag{3}$$

where A is the surface and H is the height of the opening.

A simplified method for single sided natural ventilation configurations is proposed by the University of Athens [3]. The method proposes different formulae for (a) single sided ventilation with openings at the same height and (b) single sided ventilation with openings at different levels. For both cases the air flow is due to the temperature difference between the indoor and the outdoor environment, while wind phenomena are neglected.

For the case of openings at the same height, the proposed expression is the following:

$$Q = 790\, H^{1.5} W \sqrt{\frac{\Delta T}{\overline{T}}} \quad (\mathrm{m^3/h}), \tag{4}$$

where H and W are the vertical height and the width of the opening. Also ΔT is the temperature difference between indoor and outdoor and $\overline{T}$ is the mean indoor–outdoor absolute temperature.

For configurations with openings at different heights, the method proposes the following expression:

$$Q = 1590\, K(A_1 + A_2) \sqrt{\frac{\Delta T H}{\overline{T}}} \quad (\mathrm{m^3/h}), \tag{5}$$

where A_1 and A_2 are the areas of the two openings, K is a correction factor given as a function of A_1 and A_2 and H is the vertical distance between the two openings. Also ΔT is the absolute temperature difference between indoor and outdoor and $\overline{T}$ is the mean indoor–outdoor temperature.

De Gidds and Phaff [4] have proposed an empirical correlation that integrates wind and temperature difference phenomena combined with the turbulence effects. According to the model, air flow in single sided natural ventilation configurations can be predicted by the following expression:

$$Q = 0.5\, A(C_1 V^2 + C_2 H \Delta T + C_3)^{0.5} \quad (\mathrm{m^3/s}), \tag{6}$$

where V is the meteorological wind velocity, A is the effective opening area, H is the vertical size of the opening, C_1 is a dimensionless coefficient depending on the wind, C_2 is a boundary constant and C_3 is a turbulence constant. The term C_3 is equivalent to an effective turbulence pressure that provides ventilation in the absence of stack effect or steady wind. Comparison between measured and calculated values has led to the following fitting parameters: $C_1 = 0.001$, $C_2 = 0.0035$, $C_3 = 0.01$.

As previously mentioned, simplified models cannot be considered of general validity and should always be used within the limits of their applicability.

2.1.2 *Pulsation Models*

Experimental studies on single sided ventilation configurations carried out either in wind tunnels, on scale models or in real buildings have shown that the effects of turbulence are significant in the case of single sided ventilation. Malinowski [5] has explained that the mechanism of wind-induced single opening ventilation is pulsation and wind pressure distribution by Eddy. Pulsation describes this phenomenon as an adiabatic compression and expansion of the air inside the investigated space. Cockroft and Robertson [6] have assumed an isotropic turbulence and a Gaussian probability distribution for wind velocity and flow rate and they have proposed a simple theoretical model which according to their data gives a good agreement with experimental results. Pulsation models are not appropriate for design purposes due to the non-easy availability of input data and the important limitations regarding the field of application.

2.1.3 *Computerized Fluid Dynamics Models*

CFD models are mainly used for steady-state problems to predict the temperature and velocity fields inside and the pressure field outside a building. This type of modeling is based on the solution of Navier–Stokes equations, namely the mass, momentum and thermal energy conservation equations on all points of a two- or three-dimensional grid that represents the building under investigation and its surroundings. However, for practical design assessment purposes, the use of CFD models is not yet appropriate due to the complexity of the modeling procedure, the uncertainty of the boundary conditions and the difficulty in describing the real conditions.

2.1.4 *Network Prediction Models*

Network prediction models combine the effect of wind and buoyancy to calculate pressure differences. The models are based on the mass flow balance of a zone:

$$\sum_{i_m}^{j_m} \rho_{i_m} Q_{i_m} = 0, \tag{7}$$

where Q_{i_m} is the volumetric flow rate through the ith flow path of the mth node, and ρ_{i_m} is the density of air flow through the ith flow path of the mth node (kg/m^3). For small openings and one way flow, almost all tools use the standard orifice equation to predict the air flow, Q:

$$Q = C_d A \sqrt{\frac{2|\Delta P|}{\rho}} \quad (\mathrm{m^3/s}), \tag{8}$$

where C_d is the discharge coefficient of the opening, A the flow area, ΔP is the pressure difference across the opening and ρ is the air density. In large openings flow, the discharge coefficient takes values between 0.6 and 1. An extensive review of the existing methodologies to calculate the discharge coefficient of large internal openings is given by Santamouris [7]. However, for large external openings, where the impact of the wind on the air flow is not negligible, there are no appropriate methodologies to calculate values of C_d, and this is an important source of uncertainty.

The flow through large openings is considered to be bi-directional. The neutral plane height at each opening is found by imposing $\Delta P = 0$. The flows above and below it, in m^3/s, are then given by the following relations:

$$Q_{\text{above}} = C_d W \int_{\text{NL}}^{H_t} \sqrt{\frac{2\Delta P}{\rho}} g \, dz \quad \text{and} \quad Q_{\text{below}} = C_d W \int_{H_b}^{\text{NL}} \sqrt{\frac{2\Delta P}{\rho}} g \, dz, \tag{9}$$

where H_t, H_b and NL are the heights of the opening top, bottom and neutral level, respectively.

The pressure difference across an opening connecting two zones, 1 and 2, is calculated by

$$\Delta P = P_{o1} - P_{o2} + P_{\text{dyn}} + P_{\text{stack}} \quad (\mathrm{Pa}), \tag{10}$$

where P_{o1}, P_{o2} are the reference pressures taken at the bottom of each zone, P_{dyn} is the wind-induced pressure and P_{stack} is the pressure difference induced by the stack effect. In the case of internal openings $P_{\text{dyn}} = 0$, while for exterior openings

$$P_{\text{dyn}} = 0.5 \rho C_p V^2 \quad (\mathrm{Pa}), \tag{11}$$

where C_p is the pressure coefficient and V is the wind speed at the building's height.

It should be pointed out that these models consider a steady wind blowing towards the opening and neglect the turbulent effects and the corresponding fluctuating pressures. Therefore, though the inside pressure increases as a function of the wind velocity, the ventilation rate remains constant.

PASSPORT-AIR [8] was developed within the framework of PASCOOL based on the principles of network modeling. It was compared with success to the following well-known network models: AIRNET [9], BREEZE [10], COMIS [11], ESP [12] and NORMA [13]. Further validation of the tool and improvement of its accuracy was carried out using data from the extensive experimental program of PASCOOL.

2.2 Experimental Activities in the Framework of Pascool

Experimental activities on single sided natural ventilation within the frame of PASCOOL program comprise three types of experiments:

(a) experiments in real buildings using the tracer gas decay technique;
(b) experiments in test cells using the tracer gas decay technique;
(c) experiments in PASSYS test cells using constant injection tracer gas techniques.

The general objective of these experiments was to measure the single sided ventilation air flow rates under various conditions of wind and temperature in order to derive empirical models that could be used in simulation tools.

2.2.1 Experiments in Real Buildings Using the Tracer Gas Decay Technique

Experimental activities in real buildings took place in Athens, Greece and in Madrid, Spain. The building in Athens was the Institute of Meteorology and Physics of the Atmospheric Environment in the National Observatory of Athens (NOA), a three-storey naturally ventilated office building. Two rooms on the first floor were selected for the experiments (Fig. 1). The first (room 1) has a floor area of $13.59\,m^2$ and an external window (W1) divided into five parts that

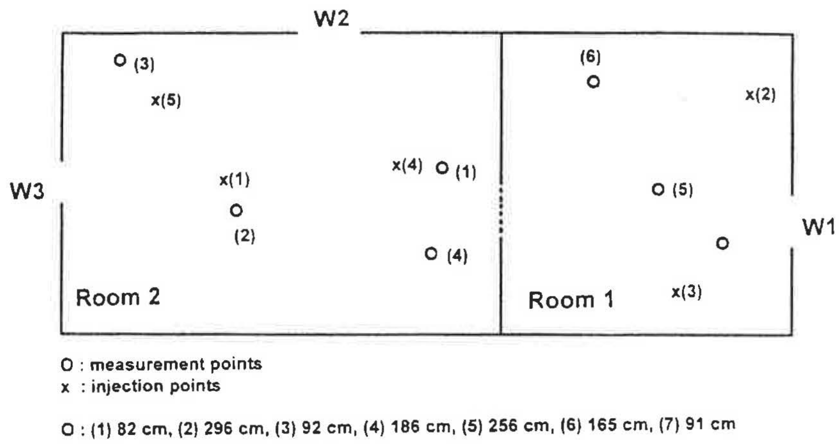

FIGURE 1 Location of the injection and measuring points–decay method (National Observatory of Athens, NOA building, Greece).

can open separately, providing the possibility to vary the opening area by opening different parts. The opening area of each part is 0.34, 0.34, 0.60, 0.60 and 0.66 m^2. The second room (room 2) has a floor area of 26.41 m^2 and has two external windows of the same opening area, 3.125 m^2. The door connecting the two rooms was kept closed during the experiments. The building in Madrid was a four-room apartment, the Mendillorri building. The rooms where the experiments took place were isolated from the rest of the building. A total of 49 experiments were carried out in the NOA building during the summer of 1993 and 1994. Eight experiments were carried out in the Mendillorri building.

Experiments were carried out according to the tracer gas decay technique, using N_2O as a tracer gas. For the period of the experiments indoor and outdoor air temperature data were available as well as wind speed and direction measurements at a 10 m height very close to the test site. In both cases the same protocol was followed.

Injection and sampling points were carefully chosen and distributed at various heights inside the space in order to supply the tracer gas homogeneously and also to monitor its spatial variation with time. Figure 1 shows the positions of the injection-sampling points during the experiments in one of the rooms of the NOA building. The sampling period was 30 s. N_2O was injected in the room, while the exterior opening was sealed. Small fans were used, in order to achieve good mixing of the gas during the injection period. The gas concentration in the room increased and when the mixing was satisfactory, the fans were turned off, the injection stopped and the window/door opened. Then concentration at every measuring point was constantly measured throughout each experiment. Further details on the setup and prevailing climatic conditions for each experiment are given in [14].

2.2.1.1 Principles of the tracer gas decay method. According to the decay method, the decrease of the tracer gas concentration is given by the following equation:

$$C(t) = C(t_0)\exp(-nt), \tag{12}$$

where $C(t)$ and $C(t_0)$ are the tracer gas concentrations at time t and at $t=0$, respectively. Also, n is the ventilation rate. The air changes per hour have been calculated for each sampling point and then the mean value for the whole room was calculated as the mean of all sampling points. Homogeneity was found to be affected by the infiltration rates, which are sensitive to the variations in the wind speed and direction and by the buoyancy effect, which gets stronger with increasing opening height. When the opening size was small, no significant homogeneity problems were encountered. As the opening size got larger, however, homogeneity was more difficult to achieve especially in cases of low wind speed. Nevertheless, even under the most difficult conditions, mixing was satisfactory.

2.2.2 *Experiments in Test Cells Using the Tracer Gas Decay Technique*

Experiments in test cell facilities were carried out in a PASSYS test cell in Athens, Greece, and in Porto, Portugal. The PASSYS test cell (Fig. 2) is a fully equipped, two room, outdoor facility for thermal and solar monitoring [15]. The experiments were carried out in the "service room", a space of 8.6 m^2 area with a length of 2.4 m and a height of 3.29 m. The room has an exterior door opening of 2.02 m^2 with a width equal to 1.01 m.

The air temperature in the room was measured by an array of sensors placed at different heights. Ambient air temperature data were provided from standard meteo stations very close to the cell as well as from protected sensors located out of the openings. Wind speed and wind

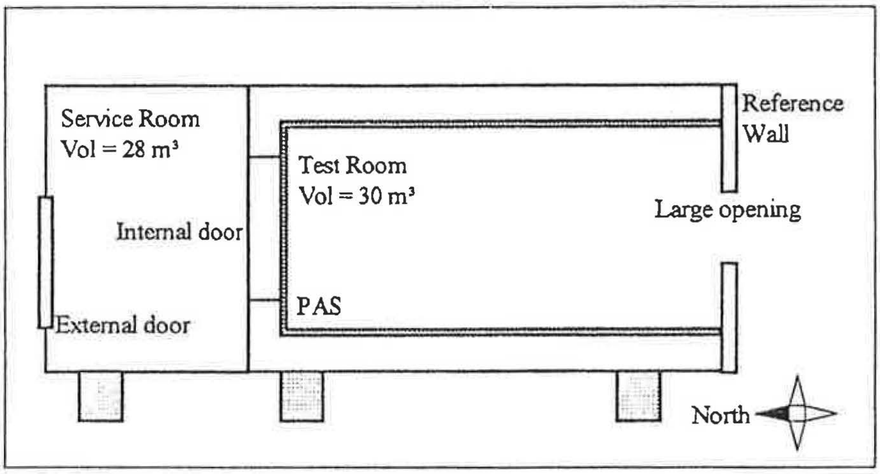

FIGURE 2 The PASSYS test cell – sectional view – at BBRI Belgium.

direction measurements were taken at a 10 m height and at a height of 1.5 and 2 m, respectively, 1 m away from the cell entrance. Hot wire anemometers are used to measure the air velocity at the opening surface. Ventilation measurements were done using the single tracer gas decay technique. N_2O was used as tracer gas.

The Porto test cell has two large openings: a south oriented window with an opening area of 2.3 m^2 and a north door with an opening area of 1.34 m^2. A total of 15 single sided ventilation experiments were carried out using CO_2 and SF_6 as tracer gasses.

2.2.3 Experiments in PASSYS Test Cells Using Constant Injection Tracer Gas Technique

Contrary to the decay technique, a continuous injection of tracer gas allows a continuous measurement of air flow rates.

Experiments in PASSYS test cells using constant injection tracer gas technique were carried out in BBRI, Belgium. Three different single sided ventilation experiments were carried out in the PASSYS test cell equipped with the Pseudo Adiabatic Shell (PAS). The PAS (Fig. 2) consists of a second shell (130 mm) at the inside of the test room walls, which allows to evaluate the heat flux leaving the cell through all the walls except the south one. The PASSYS Lightweight Reference Wall [16] was used as south wall. It consists of three layers: wood (12 mm), expanded polystyrene insulation PS30 (100 mm) and wood (12 mm) and has a window of about 1.3 m^2 in its center. The glazing was removed. This provides a large opening of approximately 1.1 m × 1.1 m.

- One room with a cold box in front of the large opening,
- one room without cold box,
- two rooms with the partition door open and without cold box.

2.2.3.1 Single sided ventilation – 1 zone (with and without cold box). An "open cold" box was placed in front of the south wall. This device provides a constant air speed (adjustable between 1 and 8 $m\,s^{-1}$) along the component at the temperature of the outside air.

The tracer gas that was used for ventilation measurements was sulfur hexafluoride (SF_6). It was injected in the test room at a constant injection rate of 0.7 ml/s. Measurements were taken every 10 min at three different zones in the test room, in the upper and lower parts of the opening and in the cold box.

The experiment lasted 1.5 days (15(20:00)–17(8:00)/11/93). Temperature and air velocity measurements were taken in the test room, at the upper and lower part of the window and in the cold box. The wind velocity in the open cold box varied from 1 to 2 $m\,s^{-1}$. The test room was continuously heated during the experiment (≈ 1000 W). Further details on the setup and prevailing climatic conditions for each experiment are given in [17].

The second experimental period lasted 3 days (19(18:00)–22(6:00)/11/93). The cold box was removed and the external window of the test room was directly exposed to the outdoor conditions. The test room of the cell was continuously heated during the experiment (≈ 2000 W). Further details on the setup and prevailing climatic conditions for each experiment are given in [17].

Two approaches were used to calculate the air flow through the external opening of the test room: The tracer gas and the heat balance approach.

2.2.3.2 Principles of the tracer gas approach. To calculate the air flow entering the test room, Q_{in} and the one leaving, Q_{out}, a system of two equations is solved:

The mass balance equation for the tracer gas:

$$\frac{dM_{SF_6}}{dt} = S_{SF_6} + Q_{in} C_{SF_6}^{in} - Q_{out} C_{SF_6}^{out} \quad (mg/s), \qquad (13)$$

where M_{SF_6} is the mass of SF_6 contained in the test room (mg), S_{SF_6} the SF_6 injection rate (mg/s), Q_{in} the air flow rate leaving the test room (m^3/s), Q_{out} the air flow rate entering the test room (m^3s), $C_{SF_6}^{in}$ the SF_6 concentration of the air flow entering the test room (mg/m^3) and $C_{SF_6}^{out}$ is the SF_6 concentration of the air flow leaving the test room (mg/m^3).

The mass balance equation for the air is

$$\frac{dM}{dt} = Q_{in}\rho_{in} - Q_{out}\rho_{out} \quad (kg/s). \tag{14}$$

where M is the mass of the air in the test room (kg), ρ_{in} the density of the air entering the cell (kg/m^3) and ρ_{out} is the density of the air leaving the cell (kg/m^3).

Assuming that the mass of air contained in the cell does not vary and that the air is an ideal gas, the latest equation yields

$$\frac{Q_{in}}{T_{in}} = \frac{Q_{out}}{T_{out}} \quad (m^3/(s\,K)), \tag{15}$$

where T_{in}, T_{out} are the temperatures of the air entering and leaving the test room, respectively (K).

The mass balance equations can then be combined to yield

$$\frac{dM_{SF_6}}{dt} = S_{SF_6} + Q_{out}\left(C_{SF_6}^{in}\frac{T_{in}}{T_{out}} - C_{SF_6}^{out}\right) \quad (mg/s). \tag{16}$$

The air flow rates can then be calculated using the mean value theorem for $\Delta T = 10$ min.

2.2.3.3 Principles of the heat balance approach. The heat balance equation for the test room is

$$\frac{dQ_h}{dt} = \Phi_{PAS} + \Phi_{heating} + \Phi_{wall} - \Phi_{ventilation} + \Phi_{sun} \quad (W), \tag{17}$$

where Q_h is the heat contained in the air and in the materials present in the test room (J), Φ_{PAS} the heat flow entering the test room through the PAS (W), $\Phi_{heating}$ the heating power provided by electrical convectors in the test room (W), Φ_{wall} the heat flow entering the test room through the reference wall (W), $\Phi_{ventilation}$ the heat leaving the test room due to ventilation (W) and Φ_{sun} is the heat flow rate by solar radiation through the opening, measured by a pyranometer mounted vertically on the south wall (W). For the experiments using the "cold box" $\Phi_{sun} = 0\,W$.

The heat flow through the cell envelope can be derived from the external and internal surface temperatures of the panels of PAS. The PAS is made of 20 panels. The heating power was measured by the electrical power measurement system provided in PASSYS cells. The variation of heat stored in the cell is given by

$$dQ_h = c\,dT \quad (J), \tag{18}$$

where c is the thermal capacity (20 000 J/K) and T the mean temperature in the test room. The heat flow density (q, W/m^2) across the reference wall was measured by heat flux sensors at two locations. The total heat flow rate was

$$\Phi_{wall} = A\frac{q_1 + q_2}{2} \quad (W), \tag{19}$$

where A is the reference wall surface (minus the opening surface).

The ventilation heat flow is related to the air flow by the following expression:

$$\Phi_{ventilation} = 0.34\,nV(T_{out} - T_{in}) \quad (W), \tag{20}$$

where nV is the air flow rate (m^3/h), T_{out} the temperature of the air flow leaving the test room (K) and T_{in} is the temperature of the air flow entering the test room (K).

The difference between the mean indoor and outdoor temperatures was smaller than the temperature difference of the air flows entering and leaving the test room (measured at the opening), for most of the time period of the experiment.

2.2.3.4 Comparison of the two approaches. A comparative presentation of the results from the two approaches is illustrated in Figs. 3 and 4 for the experiments using the "cold box" and for those without it. The confidence bands are overlapping each other during the whole period of the experiments. SF_6 concentrations were found to fluctuate less

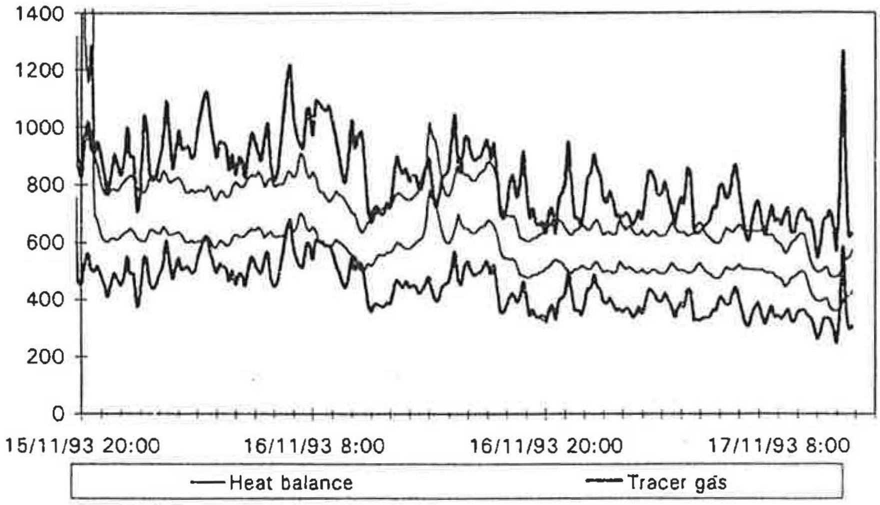

FIGURE 3 Comparison of the air flows derived by the tracer gas and the heat balance approaches, for the experiment in a PASSYS test cell with PAS and a cold box.

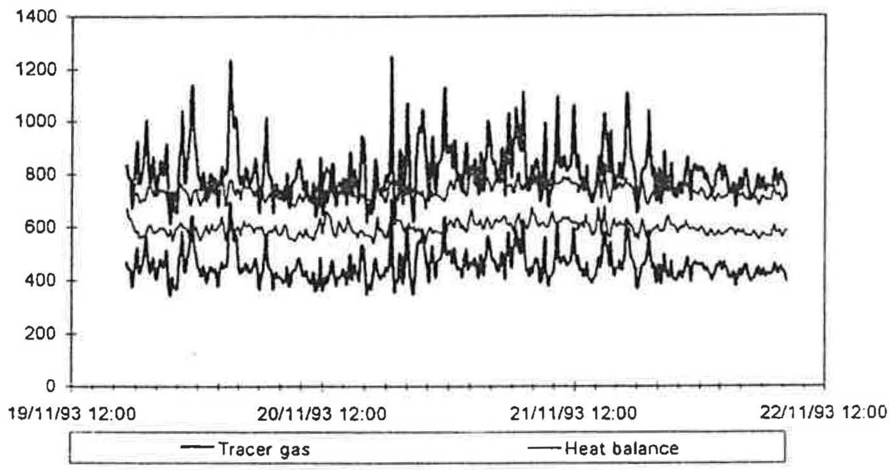

FIGURE 4 Comparison of the air flows derived by the tracer gas and the heat balance approaches, for the experiment in a PASSYS test cell with PAS (2 room, no cold box).

during the cold box experiments. This was expected since the "artificial wind" provided by the cold box is obviously more stable than the "real wind" the large opening was exposed to during these experiments. The wind direction, however, was almost constant during the measurement period (NNE or 200° from the normal to the opening).

In both cases, the heat balance approach provided a less fluctuating and more accurate flow.

2.2.4 Single Sided Ventilation – Two Rooms with the Partition Door Open (no Cold Box)

The objective of this experiment was to see whether the single sided ventilation of one zone has an impact on the ventilation of an adjacent zone, linked to it by a large internal opening. This experiment was performed in a PASSYS test cell with the PAS, with the partition door between the service room and the test room open. The test room was ventilated through the window on the south wall. Heating and cooling systems were used in order to get large variations of the temperature differences through both openings. Further details on the setup are given in [17].

Two tracer gasses were used. R_{22} was continuously injected in the service room and SF_6 in the test room. At total of eight injection points were distributed in the rooms.

The obtained air flow rates through the south opening as well as through the internal opening are given in Fig. 5. The air flow rate through the large external opening was evaluated with an accuracy of about 15%, while the accuracy of the air flow through the internal opening was estimated to be about 25%.

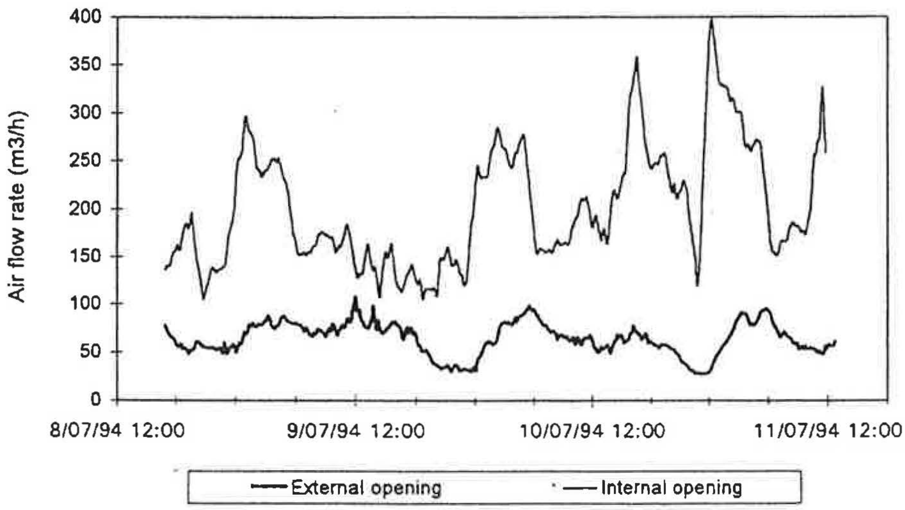

FIGURE 5 Air flow through external and internal opening of the test cell in $m^3 h^{-1}$.

2.3 Validation of Existing Models Using Experimental Data

In order to assess the accuracy of the existing models to predict air flow in single sided-natural ventilation configurations, the models described in the previous sections have been used to calculate the air flow for some of the experiments and the theoretical results have been compared with the corresponding experimental values. Comparisons have been performed for the experiments carried out at the NOA building as well as in the PASSYS test cells.

Two of the modeling approaches described in Section 2.1 were used in order to predict the air flow rates for the experiments described in Section 2.2: the simplified methods and the network models. The theoretical results were compared with the corresponding experimental values.

2.3.1 *Simplified Methods*

The whole comparison exercise has shown that, in general, simplified methods do not predict accurately the air flow for single sided ventilation configurations in the cases, where the wind forces are dominant. The main reason is due to the fact that the impact of the wind is not correctly taken into account in combination with the flow due to temperature difference.

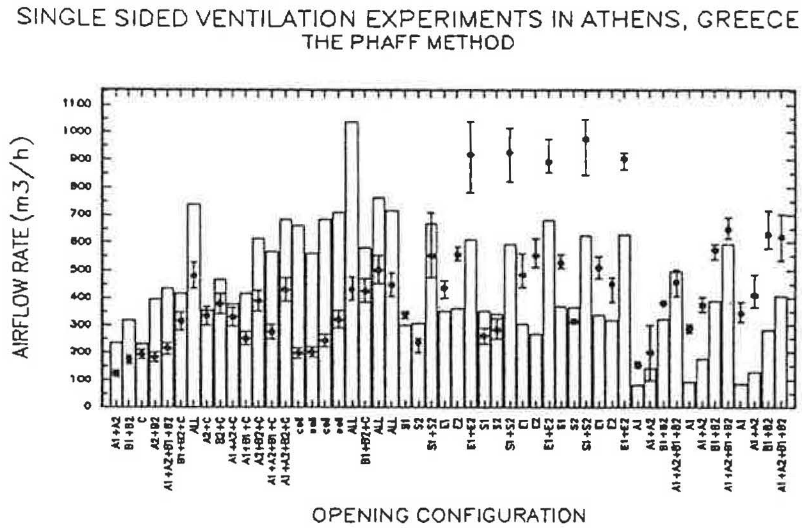

FIGURE 6 Single sided ventilation experiments in Athens, Greece – The Phaff method.

Using the de Gids and Phaff method, the air flow rate for each of the previously indicated experiments has been calculated. The values obtained are given in Fig. 6 in comparison with the measured ones. As shown, the agreement between the calculated and experimental values is not satisfactory. The correlation coefficient between the two sets of data is calculated equal to 0.37. The same was found for the British Standards Method as well as for the one proposed by the University of Athens.

2.3.2 *Network Models*

Four network models, COMIS [11], BREEZE [10], AIRNET [9] and PASSPORT-AIR [8] have been used to predict air flow rates for all experiments carried out at the NOA building as well as for the PASSYS test cell experiments, where the decay method was used. It was found that all existing tools predict almost the same values. The correlation coefficient for the predictions of the four network tools are between 0.97 and 0.99 [14]. This result was expected as all tools use almost the same algorithms and techniques to predict air flow. However, comparison with experimental results has shown that there is not a good agreement. The calculated as well as the measured values are given in Fig. 7. The correlation coefficient between the predictions of network

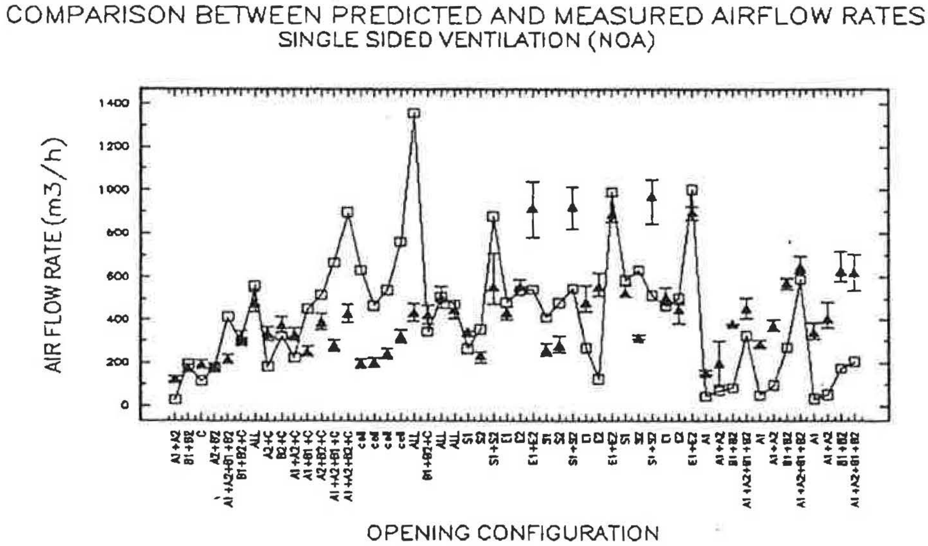

FIGURE 7 Comparison of the experimental values with predictions from AIRNET, COMIS, BREEZE and PASSPORT-AIR.

models and experimental results was found to be close to 0.4. The same was proved for the experiments in the BBRI test cells.

Further analysis of the Greek experiments using Warren plots [14], has shown that the impact of the wind was more important than the impact of buoyant forces. Indeed, these experiments were characterized by important wind speeds and small indoor–outdoor temperature differences. These are common characteristics of naturally ventilated buildings in hot climates. However, the theory of network models practically neglects the effect of the wind in the case of single sided ventilation. In an attempt to improve the accuracy of network models in the case of inertia-dominated single sided ventilation, new models were developed: the CF model and the multi-term model.

2.3.2.1 The CF model. The CF model was the product of an attempt to study if the observed differences between the experimental and predicted values can be correlated with indices describing the relative importance of the inertia and gravitational forces. This was achieved by the following procedure:

PASSPORT-Air has been used to predict the air flow for all the single sided ventilation experiments carried out in Greece. For all the tools a discharge coefficient, C_d, equal to 1 has been used. Then, for each experiment, a correction coefficient, CF, is calculated. This coefficient is defined as

$$\mathrm{CF} = \frac{\text{Mean Measured Air Flow}}{\text{Predicted Air Flow}}. \tag{21}$$

The correction coefficient, CF, as calculated for all the experiments is correlated with the Archimedes number, Ar_D:

$$\mathrm{Ar}_D = \frac{\mathrm{Gr}}{\mathrm{Re}_D^2} = \frac{gH^3\Delta T}{TV^2D^2}, \tag{22}$$

where $\mathrm{Gr} = g\Delta T H^3/(T\nu^2)$, the Grashof number and $\mathrm{Re}_D = VD/\nu$, the Reynolds number. The characteristic lengths H and D in the Gr and Re_D numbers are the opening height and the room "depth", respectively. The room "depth" is defined as the distance between the wall where the opening(s) is (are) and the wall opposite to it in the single side ventilated zone.

It is found that there is a very satisfactory correlation between both parameters, Fig. 8, and therefore the CF coefficient can be calculated, for single sided ventilation configurations, from the following expression:

$$CF = 0.08\left(\frac{Gr}{Re_D^2}\right)^{-0.38}. \tag{23}$$

The r^2 of the regression is calculated equal to 0.73.

Equation (22) predicts with sufficient accuracy the correction coefficient CF, especially for experiments which are not characterized by an important fluctuation of the wind speed and incidence angle during the experiment.

The above-presented model has been derived from experiments where ventilation was dominated by inertia forces. If the correction factor takes values under the limit of 0.6, then CF is taken equal to 0.6.

In order to assess the accuracy of the proposed methodology the predictions of PASSPORT-AIR with and without using the correction coefficient have been compared with the experimental values. It was found that the correlation coefficient between the experimental set of data and the predictions of PASSPORT-AIR without using the

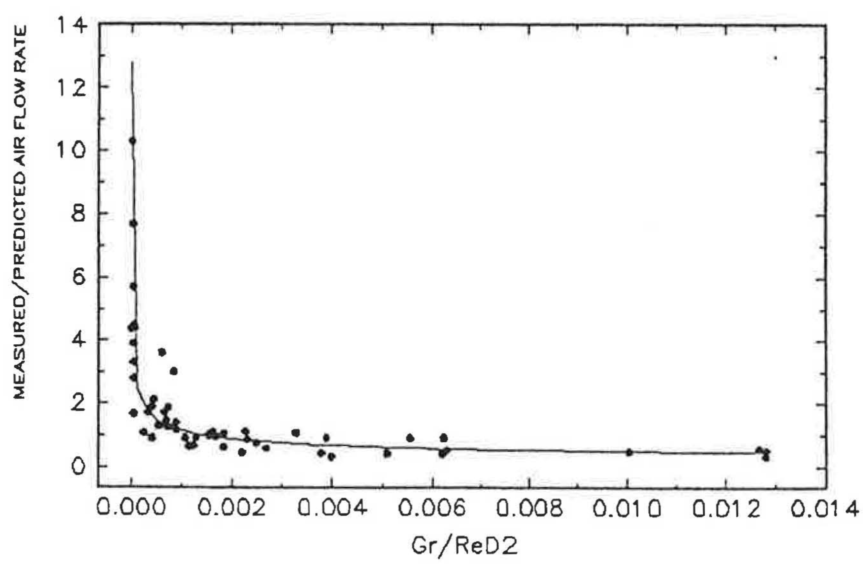

FIGURE 8 Correction coefficients as a function of Gr/Re_D^2 – (NOA building, Greece).

Correction Factor is close to 0.4, while the corresponding correlation coefficient when CF is used was found equal to 0.75. Figure 9 gives the difference between the experimental measurements and the PASSPORT predictions with and without the use of the correction coefficient. Simulation results for the experiments that were carried out in the Mendillori building using PASSPORT-AIR with and without Correction Factor were compared with experimental values. The correlation coefficient between predicted and measured values was initially close to 0.50 and it became 0.82 when the Correction Factor was used. The same was observed for the experiment described in Section 2.2.3.1. The correlation coefficient between predicted and measured values was initially close to 0.72 and it became 0.86 when the Correction Factor was used. Use of the Correction Factor improves significantly the predictions of PASSPORT-AIR and, in general, of the network models.

The CF model was based on experiments characterized by small temperature difference and medium to high wind speed. The wind speed varied from 2 to 10 m s^{-1} and temperature differences from 0.5–8°C. The room depth varied from 3 to 7 m. The prevailing wind direction during the experiments varied from $-60°$ to $60°$ from the vertical to the opening.

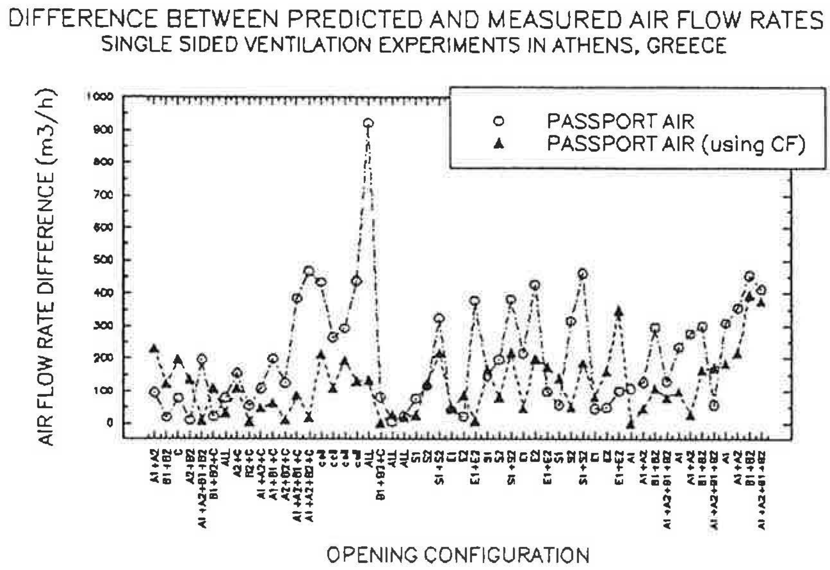

FIGURE 9 Comparison of PASSPORT-AIR predictions with and without the correction coefficient to experimental results (single sided (no cold box) ventilation experiment in BBRI).

2.3.2.2 The multi-term model. This model was derived from the experiments carried out in the BBRI PASSYS test cell. According to the model, the air flow rate, Q through a single external opening is

$$Q = \sqrt{Q^2_{\text{network}}(C_d \Delta T \ldots) + (\alpha A V)^2 + (\beta A)^2} \quad (\text{m}^3/\text{h}). \qquad (24)$$

where Q is the air flow rate through the external opening (m^3/h), Q_{network} is the air flow rate calculated by network models (m^3/h) with a discharge coefficient of 0.66, A the surface of the opening (m^2) and V is the wind speed at a 10 m height (m/s). The network model term, Q_{network}, takes into account the thermal effect. It depends on opening characteristics (coefficient of discharge, height, width), on the air temperature difference with the outside and on the vertical air temperature gradient in the room. The constant term βA is due to turbulent air movements which are present, even when there is no wind and no temperature difference. The term $\alpha A V$ takes into account the effect of the wind on the single sided ventilation. Table I shows the 95% confidence intervals obtained for α, β and C_d coefficients after identification on experimental data. The correlation coefficient between experimental and simulated values is also given.

Figure 10 shows a comparison between the measured values of air flow rates and those calculated by the empirical model using measured temperatures and wind velocities. The average relative difference between the predicted and the measured values is 13% (for both measurement periods). As the thermal part is quite well simulated by network models, it is interesting to look at the difference between predictions and measurements for periods with wind. Taking into account periods with wind stronger than 0.1 m/s provides an average relative difference of 17%.

It must be stressed that the values given for model parameters are valid for the particular experiment carried out and they are related to

TABLE I Results for the fitting coefficients of model 2.46 (95% confidence intervals)

C_d (discharge coefficient)	[0.63–0.69]
β (turbulent term)	[70–99]
α (wind term)	[80–86]
r (correlation coefficient)	[0.91–0.93]

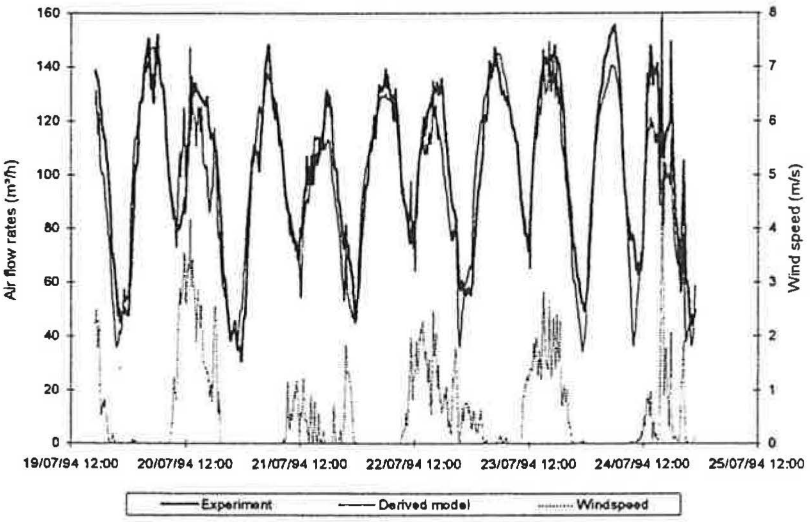

FIGURE 10 Comparison between measured and predicted air flow rates for the multi-term model (second measurement period).

the particular environment of the investigated test cell. Different environments certainly need different values. The model was derived from particular experimental conditions (prevailing wind direction: 200° off the normal to the opening) and this is certainly a limitation to its applicability.

3 CROSS VENTILATION STUDIES IN PASCOOL

In most of natural ventilation applications, a real improvement of air motion can be observed when a cross ventilation can be induced. This is the reason why most of the scientists dealing with natural ventilation focus on this particular aspect. Various approaches have been proposed in the literature in order to predict cross ventilation flow rates through buildings. Mainly based on empirical models, they are usually difficult to extend to general configuration. Cross ventilation experiments in PASCOOL can be divided into two categories. First of all experiments were carried out in real buildings in order to check experimental protocols and qualify the results obtained by PASSPORT-AIR when simulating these experiments. Then, a specific experiment has been carried out in Lausanne in order to study the cross natural ventilation due to temperature differences between indoor and outdoor during the night.

3.1 Review of Cross Ventilation Models

Cross ventilation models are divided into two categories: global air flow prediction models and velocity coefficient approaches. The first give results on the impact of cross ventilation on the subjects of energy conservation and cooling. The second category deals with the impact on occupants comfort.

A first simple model to predict cross ventilation has been proposed by Aynsley [17]. Assuming two main openings on the two facades of a building (Fig. 11), Aynsley uses the definition of the pressure coefficients C_{p_1} and C_{p_2} on each facade to calculate the flow rate of air through the building. Assuming a mass flow conservation between the two large openings leads to the flow expression

$$Q = \sqrt{\frac{(C_{p_1} - C_{p_2})}{1/(A_1^2 \cdot C_{d_1}^2) + 1/(A_2^2 \cdot C_{d_2}^2)}} \cdot V_z; \tag{25}$$

C_{d_1} and C_{d_2} are discharge coefficients given as functions of the opening configuration. A_1 and A_2 are the respective areas of openings 1 and 2, and V_z the reference wind velocity used for the pressure coefficient definition. This approach has been generalized by Aynsley to n openings in series:

$$Q = \sqrt{\frac{(C_{p_1} - C_{p_2})}{1/(A_1^2 \cdot C_{d_1}^2) + \cdots + 1/(A_n^2 \cdot C_{d_n}^2)}} \cdot V_z. \tag{26}$$

The main interest of this method is its simplicity and efficiency to predict very quickly the order of magnitude of the global air flow rate

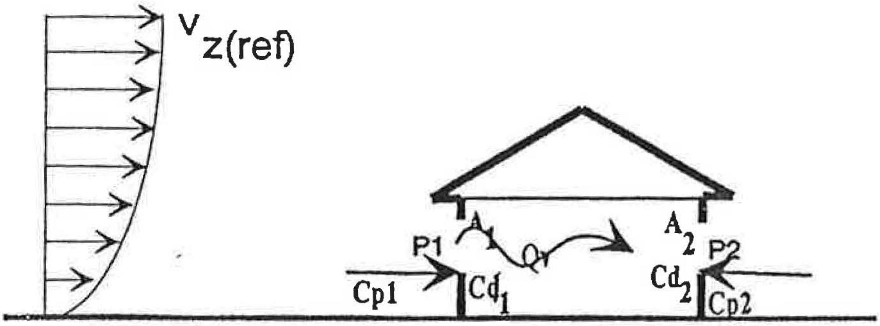

FIGURE 11 Basic model for cross ventilation [18].

through a building in a cross ventilation configuration. It is clear that this model can only give a rough estimate of the ventilation rates.

Based on the similarity of cross ventilation to air flow through ducts, proved by wind tunnel experiments, Murakami *et al.* [19] proposed a simplified model based on the general concept of the energy presentation law (Power Balance Law), as suggested by Guffey and Fraser [20] for duct junctions.

The necessity of predicting indoor air velocities has led to empirical models that focus on a comfort global approach.

Givoni [21] reports various experiments with different configurations. He remarks that in the case of cross ventilation, he obtains a higher ventilation rate when the larger opening is located on the downwind facade and proposes a general correlation when the upwind opening and downwind opening are identical. The average velocity inside the room is given by

$$\overline{V}_i = 0.45(1 - e^{-3.84x})\overline{V}_z, \qquad (27)$$

where $\overline{V}_i$ is the average indoor air velocity, x the area ratio between the opening and the facade and $\overline{V}_z$ is the reference external wind velocity. This correlation is limited to a cubic room in cross ventilation conditions.

Aynsley [18] derives the average air velocity by dividing the flow rate by the section of the air flow tube:

$$\overline{V}_i = \frac{Q}{A} \quad (\mathrm{m\,s^{-1}}), \qquad (28)$$

where Q is the air flow rate and A is the section of the air flow tube normal to the direction of the flow.

In his Ph.D. Thesis, Gouin [22] defines a set of simple coefficients in order to characterize the natural ventilation of a building. This study uses wind tunnel experiments for different building configurations. In each model, the velocity is measured in eight different locations and a statistical evaluation is proposed using the four coefficients

$$C_{\overline{V}} = \frac{1}{8}\sum_{i=1}^{8} \frac{\overline{V}}{V_{\mathrm{ref},}} \quad \text{the global ventilation coefficient,} \qquad (29)$$

$$C_v = \frac{1}{8}\sum_{i=1}^{8}\frac{\sigma}{\sigma_{\mathrm{ref}_i}} \quad \text{the global standard deviation of velocities,} \tag{30}$$

$$C_{v\max} = \left(\frac{\overline{V}_i}{V_{\mathrm{ref}_i}}\right)_{\max} \quad \text{the mean maximum velocity coefficient,} \tag{31}$$

$$\sigma C_{\overline{vi}} = \sigma \cdot \left(\frac{\overline{V}_i}{V_{\mathrm{ref}_i}}\right) \quad \text{the spatial standard deviation of mean velocity.} \tag{32}$$

where V_{ref_i} represents the reference velocity of wind. Using this set of coefficients, a qualitative estimation of natural ventilation can be proposed. Thirty-six different configurations of single family models have been tested varying the slope of the roof, the repartition of openings on the two facades or on lateral walls, changing the partition location inside the model, and varying the wind incidence. General results have been obtained by Gouin [22], and general guidelines have been defined in order to improve natural ventilation efficiency in buildings.

The empirical model developed by Ernest *et al.* [23] is based on a comfort global approach and focusses on defining correlations between outdoor and indoor environments. Even if his results are restricted to the limits imposed by the configuration studied by Ernest *et al.* [23], the way of connecting the velocity coefficients to pressure coefficients is of special interest because of the numerous studies already existing on C_p coefficients in very different configurations.

The main problem is that the limits of each of the approaches described so far are not well defined. Even the physical conditions necessary are not given and finally it is very difficult to apply one or the other of these methods with a certain confidence. To check the validity of existing models cross ventilation experiments were carried out within the framework of PASCOOL project.

3.2 Experimental Program of Cross Ventilation in PASCOOL

Within the framework of PASCOOL CEC Research Program, experiments were carried out in order to study the efficiency of cross ventilation, in test cell facility (PASSYS test at BBRI) or at the National Observatory of Athens, and in real various scale buildings (MENDILLORI building in Spain, LESO Building at Lausanne) during the summer period.

3.2.1 *Experiments in Athens and BBRI: Aynsley and Givoni Models Evaluation*

Cross ventilation experiments were carried out in rooms 1 and 2 of the NOA building that have been described in Fig. 12 which shows the two openings in room 2. Cross ventilation in one zone was studied in room 2. To study cross ventilation in 2-zones room 1 and 2 were interconnected by opening the door that links them. The door has an opening area of $2\,m^2$. The tracer gas decay technique was followed using N_2O as a tracer gas.

Uniform gas concentration was achieved by using small fans dispersed at various heights all over the two zones. Five injection and seven measurement points were used. Three of the injection points were in room 2 and two in room 1. Four measurement points were in room 2 and three in room 1. The thermal performance of both rooms, where the ventilation experiments took place, was constantly monitored. Surface temperature on all internal and external surfaces of each room was monitored by PT100 sensors. Ambient temperature measurements were provided by the meteo station of the National Observatory. Wind speed and direction measurements were taken at a height of 18 m.

In Table II, the average air changes per hour (ACH). as well as the average indoor–outdoor temperature difference (ΔT) for cross

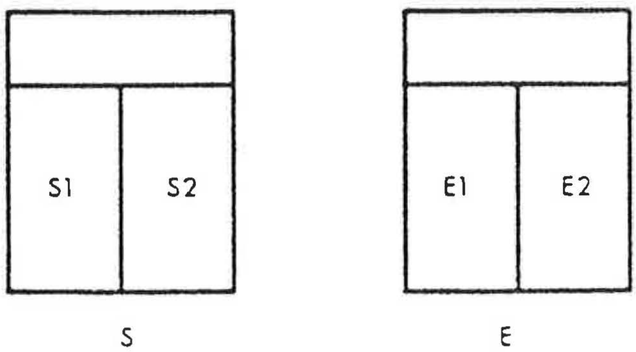

FIGURE 12 Details of the east and south window of zone B.

TABLE II Experimental data (National Observatory of Athens)

Description	*ACH*	$\Delta T = T_{in} - T_{out}$	*WS* (m/s)	*WD* (*degrees from north*)
S2 + E1	12.76	1.34	3.76	251.78
S2 + E1	11.79	0.32	4.07	242.27
S2 + E1	16.50	0.96	4.41	254.57

ventilation in zone 1 are given. In single zone configuration, the discharge coefficients (Eq. (25)) are identical. Using Aynsley model [18] (Eq. (25)) we are able to identify the discharge coefficients of the openings in this configuration. Figure 15 shows the obtained results. The discharge coefficient is around 0.22 and does not seem to be influenced by the temperature difference between outdoor and indoor air.

For the 2-zones configuration, we obtained $\tau_2 = 1540\,\mathrm{s}$ (τ is a time constant) for room 2 (volume $VR2 = 11\,885\,\mathrm{m}^3$) and $\tau_1 = 1200\,\mathrm{s}$ for room 1 (volume $VR1 = 11\,885\,\mathrm{m}^3$). We observe on Figs. 13 and 14 that τ does not vary with the altitude. This result shows that the homogeneity of the tracer gas is very good, and stratification is not significant in this case. This result is not in agreement with those obtained by Murakami *et al.* [19] in wind tunnel experiments which show an inertial flow within the cell.

The PASSYS test cell facility of BBRI has been used for a second kind of experiment. For this experiment the glazing of the reference wall of the PASSYS test cell was removed. The internal door was open as well as the external one. During this cross ventilation measurement sulfur hexafluoride was injected in the test room and nitrous oxide in the service room. The B&K tracer gas equipment allows to take a set of measurements (six locations) more or less every 9 min. All the instrumentation of the PASSYS test cell is at 1 min intervals (scanned) by the SADAT acquisition system. A common time step of 10 min was chosen. In order to analyze the data it is then necessary to interpolate concentrations at each location at the same time [2].

Figure 16 shows the evolution of concentration (SF_6 and N_2O) in sampling point 2. The fluctuation is important, and the time step value is 10 min. In these conditions, it is very difficult to appreciate the tracer gas evolution in the test cell. But measurement of data from wind velocity (a proximity of the window, and at 18 m), gives a good correlation

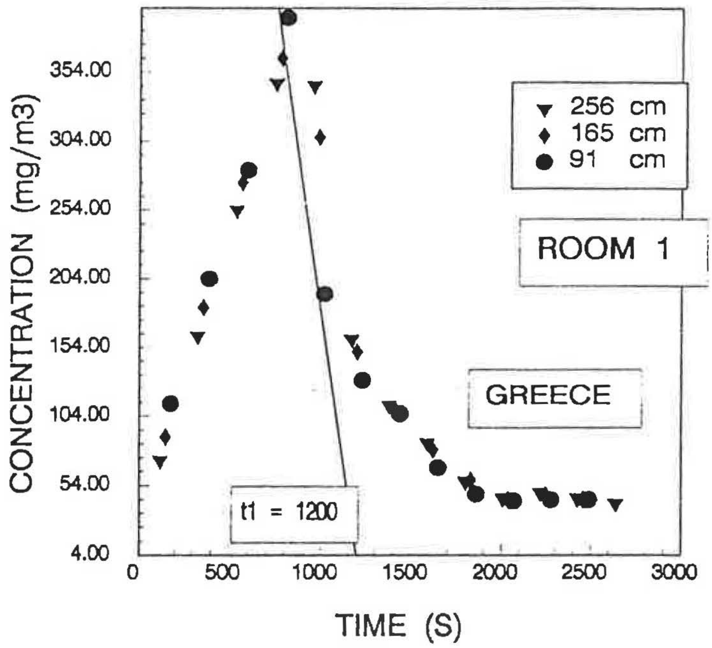

FIGURE 13 Cross ventilation in the National Observatory of Athens. Decay technique in room 1.

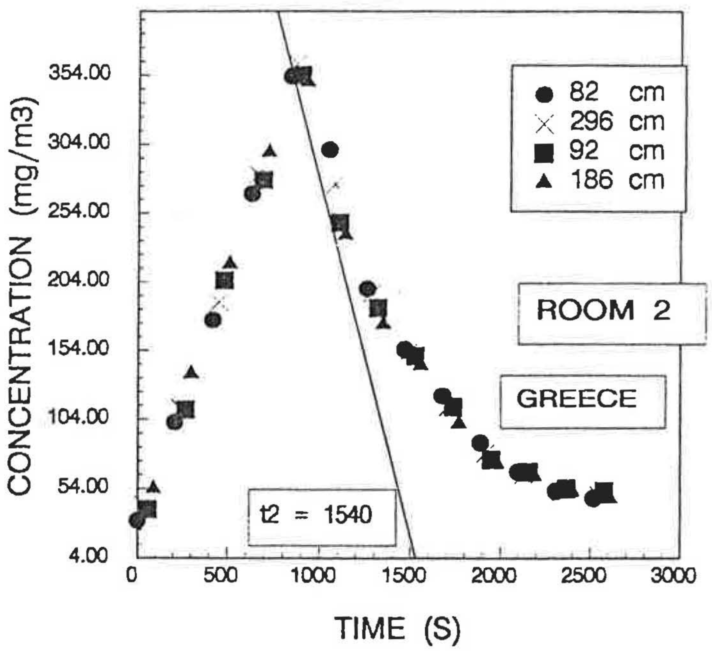

FIGURE 14 Cross ventilation in the National Observatory of Athens. Decay technique in room 2.

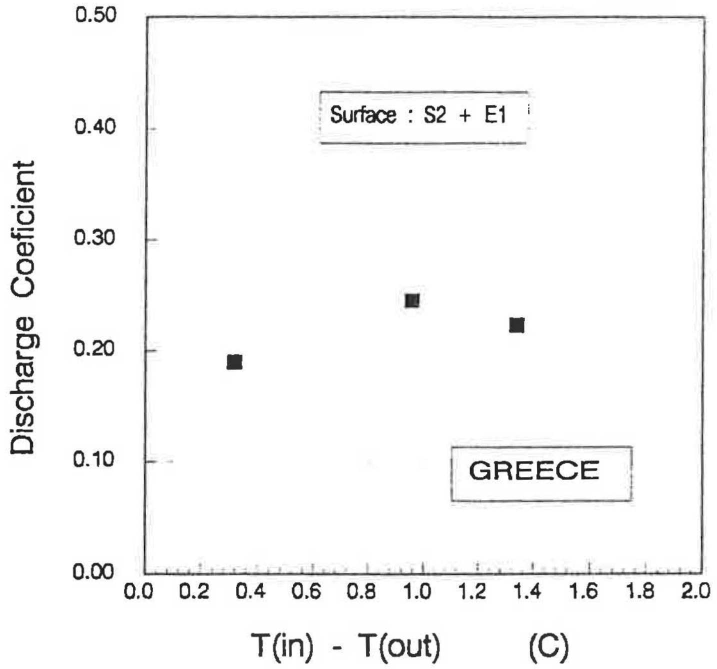

FIGURE 15 Discharge coefficient. $C_d = F\{T(\text{in}) - T(\text{out})\}$.

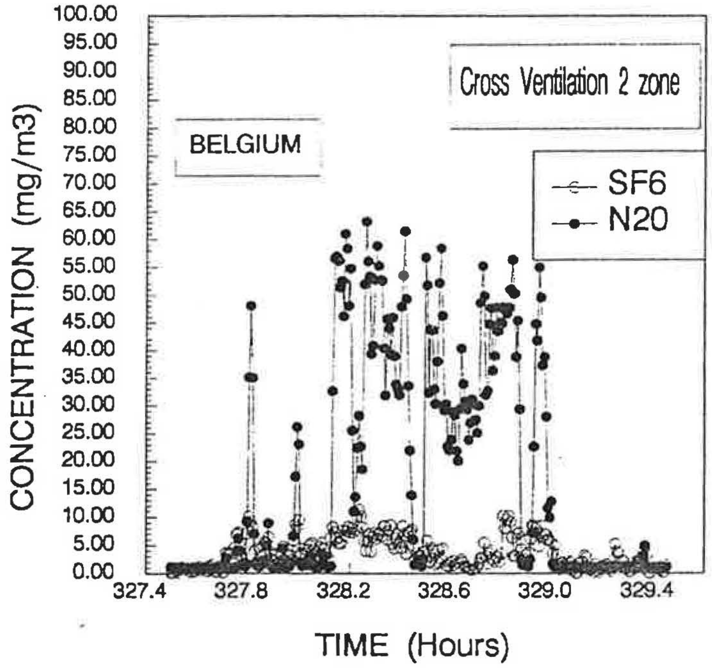

FIGURE 16 Concentration in sampling 2 (mg/m^3), in the BBRI test room.

between the outdoor wind and the velocity of air flowing through the window (Fig. 17). The Givoni's model [21] gives $V_i = f(V_z)$. Figure 18 shows a heavy cloud of points around Givoni's correlation. This figure enables us to propose a correlation ($V_i = 0.45(1 - \exp(-3.84X))V_z$) where V_i is the average indoor air velocity, X is the area ratio between the opening and the facade, and V_z is the reference external wind velocity, even if the fluctuations for 10 min time step lead to a noisy signal.

3.2.2 Night Natural Cross Ventilation Studies in the LESO Building

Three measurement campaigns on the LESO building (Fig. 19) have been performed with the objective to test the validity of simple air flow models based on the Bernoulli equation. The LESO building is well suited for this type of experiments. The staircase acts as a 12 m high chimney giving the opportunity to work with openings at different levels above ground. The building comprises three levels with offices. The staircase extends from level − 1 (basement) to level +3 (sunspace

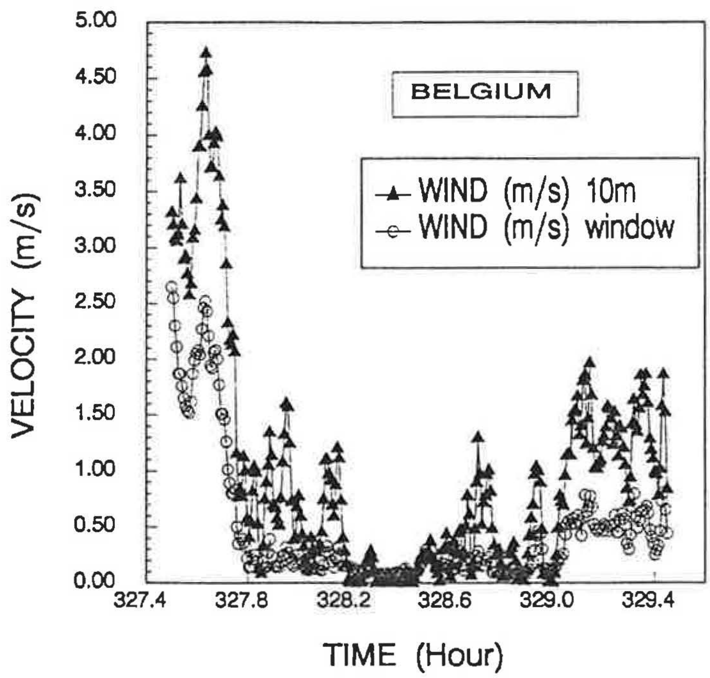

FIGURE 17 $V_i = F(\text{time})$ and $V_z = F(\text{time})$ (BBRI data, Belgium).

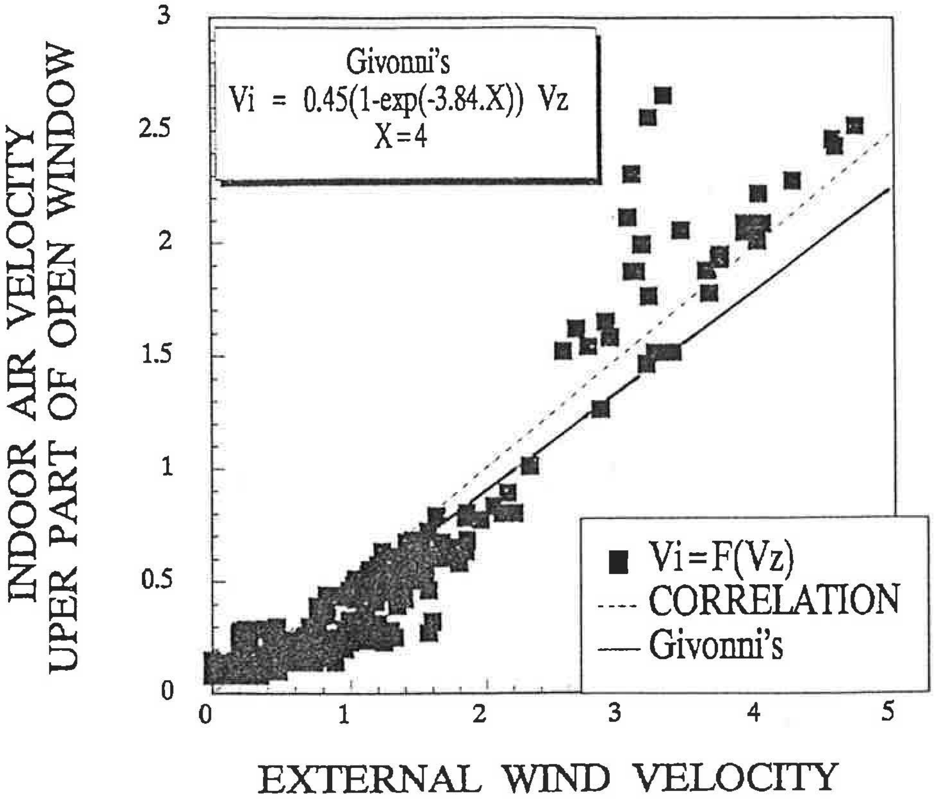

FIGURE 18 $V_i = f(V_z)$ Givoni's model (BBRI data, Belgium).

at roof level). The experiments are performed in the six central offices (003, 004, 103, 104, 203, 204). The exhaust opening (roof door facing east, 0.90 m × 1.98 m) is the same for all experiments. There are three types of experiments:

(A) Leakage and permeability of the envelope (three experiments with different inside–outside temperature differences).
(B) One top opening and one bottom opening (several experiments with various temperature differences, opening levels, or opening areas).
(C) One top opening and several bottom openings in parallel or in series.

Experiment A: building leakage. All doors and windows were closed except the top opening which stayed wide open. The measurement of the outside and inside air temperatures and the height of the NPL

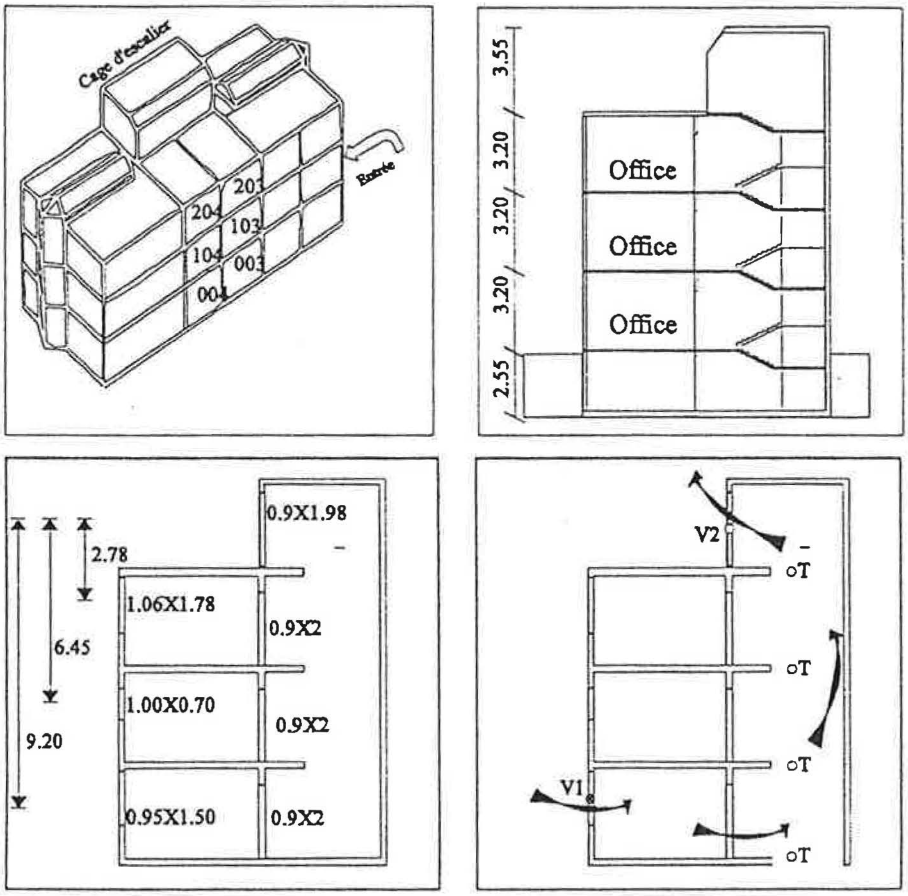

FIGURE 19 The LESO building (Florentzos and Van der Maas, 1994).

(Neutral Pressure Level) allows to calculate the leakage using formula (34):

$$m'_{\rm N}\left[\left(\frac{Z_{\rm n}}{H}\right)^{3/2}-\left(\frac{\rho_i}{\rho_0}\right)^{1/2}\left(1-\frac{Z_{\rm n}}{H}\right)^{3/2}\right]+m'_{\rm S}=0, \tag{33}$$

where $Z_{\rm n}$ is the vertical position of the neutral plane (m), ρ_i the air density (kg/m^3) for zone i, and ρ_0 is the air density reference (kg/m^3) (Fig. 20). The temperatures are measured at 1 m from the bottom and far away (several meters) from the opening. The temperature differences between inside and outside were different for the three tests, being typically 9°C, 10°C and 14°C. The various experiments have

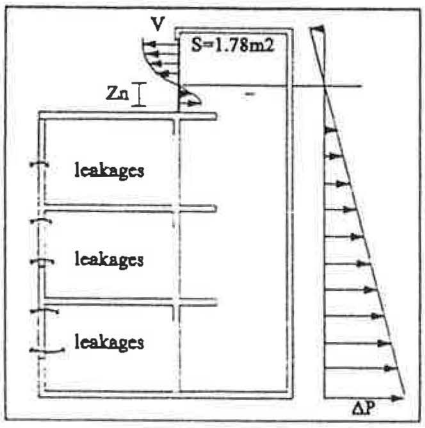

FIGURE 20 The neutral pressure level (Zn) in the openings (Florentzos and Van der Maas, 1994).

been performed early in the morning (6–9 h) to minimize the wind influence (the wind velocity was in the range 20–40 cm/s, wind direction N–NW). The offices are south-oriented and therefore all inlet openings are south-oriented apart from the exhaust which is facing east. The velocity measurements were made using a DANTEC anemometer (±2.5%) and an ultrasonic anemometer of Gill Instruments (±3%). Temperature measurements in the staircase were made at each level with ventilated Pt100 probes (±0.3 K). The NPL in the openings is detected with "Dräger" smoke puffers [24].

With the measurement of two velocities in the opening (one above and one below the NPL) an estimate of the flow rate can be made assuming a parabolic velocity profile. This flow rate is compared with the flow rate obtained from detailed velocity profile measurements and the difference in the results was less than 25% (Table III). Existing leakage data of the LESO obtained by the fan pressurization technique over the pressure interval 20–50 Pa, were fitted to

$$Q = (740 \pm 250)\Delta P^{0.6} \quad (\mathrm{m^3\,h^{-1}}). \tag{34}$$

Extrapolation to low pressures would give an equivalent leakage area of 0.24 m^2 which is close to the value obtained with the NPL method. The model is sensitive for the measurement of the position of the NPL which, when the air flow is stable, can be determined up to a few cm precision. The temperature measurement has less influence on the result. In order to have stable air flow and to be able to calculate the flow

TABLE III Experimental results for experiment A: equivalent leakage areas determined with the neutral pressure level (NPL) method

Experiment ⇒	*A*1	*A*2	*A*3	*A*4	*A*5
$T_i \pm 0.5$ [°C]	22.1	20	20.5	20.5	26.2
$T_e \pm 0.5$ [°C]	13.5	10.3	5.1	12	19.1
$H_n \pm 0.05$ [m]	0.78	0.8	0.82	0.8	0.8
m[†] ± 0.06 [kg/s]	0.18	0.17	0.19	0.16	0.15
DR_{max} ($Z=0$) [Pa]	0.34	0.38	0.63	0.33	0.26
A equiv. at $Z=0$ [m]	0.20	0.18	0.16	0.18	0.19

[†]Formula (33).

driving pressure from the stack effect, the experiment was done under no-wind conditions. It is worth noting, however, that the NPL method can also be used to determine net flow rates through open door ways when driven by mechanical ventilation or stable wind.

Experiment B: ventilation with two openings. The experiment is realized with different height, openings and inside–outside temperature differences. The reference height is the center of the bottom opening.

$$h_2 = \frac{H}{1 + [(C_{d_2}A_2/C_{d_1}A_1)^2(\rho_2/\rho_1)(\Delta\rho_t/\Delta\rho_b)]} \quad (\mathrm{m}), \tag{35}$$

$$u_k = C_{\nu_k}\sqrt{gh_k\frac{\Delta T}{T}} \quad (\mathrm{m\,s^{-1}}), \tag{36}$$

$$\dot{m}_k = \rho A_k C_{d_k}\sqrt{2gh_k\frac{\Delta T}{T}} \quad (\mathrm{m^3\,h^{-1}}), \tag{37}$$

where k is the index of the opening.

The experimental results (Table IV) give a velocity coefficient of $C_\nu = 0.7$. An exception is the last case where the limits of the model are reached because the stack height is too small compared to the vertical opening size.

For the case where the openings are at the top and bottom of the building (cases 1–5) the mass balance is good. For the case where the bottom opening is on the first or second floor, the flow in the exhaust opening is different from what was calculated. The difference is of the order of the leakages measured in the first experiment.

TABLE IV Experimental results for experiment B: single flow path with two openings

Experiment ⇒	*B*1	*B*2	*B*3	*B*4	*B*5	*B*6	*B*7
H total	9.5	9.2	9.2	9.2	9.2	6.45	2.76
S_1 [m^2]	1.88	1.43	1.43	0.68	0.3	0.7	1.68
S_2 [m^2]	1.78	1.78	1.78	1.78	1.78	1.78	1.78
C_{v_1}	0.7	0.7	0.7	0.7	0.7	0.7	0.55
C_{v_2}	0.7	0.7	0.7	0.7	0.7	0.7	0.7
T_i [°C]	16.2	22.1	18.9	22.1	22.1	18.9	18.5
T_e [°C]	6.0	13.0	9.1	13.0	13.5	9.1	10.0
Z_n† [m]	4.41	5.51	5.54	8.01	8.94	5.56	1.76
Z_1 [m]	0.0	0.0	0.0	0.0	0.0	−0.2	0.0
V_1‡ measured [m/s]	1.3	1.31	1.39	1.58	1.63	1.32	0.64
V_1 calculated [m/s]	1.34	1.31	1.36	1.57	1.61	1.39	0.66
Difference	3%	0%	−2%	−1%	−1%	5%	3%
Z_2 [m]	9.5	9.2	9.9	9.2	9.2	7.15	2.76
V_2‡ measured [°C]	1.4	1.0	1.08	0.59		0.72	0.8
V_2 calculated [°C]	1.4	1.05	1.19	0.59		0.86	0.69
Difference	0%	4%	9%	1%		16%	−16%
m_1¶ [kg/s]	2.53	1.87	2.03	1.08		1.10	1.39
m_2¶ [kg/s]	2.49	1.74	1.90	1.03		1.27	1.41
$m_2 - m_1$ (flow balance)	−0.04	−0.13	−0.12	−0.05		0.17	0.02

† Formula (35).
‡ Formula (36).
¶ Formula (37).

Experiment C: openings in series or in parallel. The experiments were done in a first floor office. In the first experiment the window and the door are opened in series. In the second and third experiments a wood board is partly obstructing the door opening, and the openings in series have areas 0.7 and 0.9 m^2, respectively. The fourth experiment is with two windows opened in parallel $0.7 + 0.7\,\mathrm{m}^2$ with the wide open door in series.

The velocity coefficients used in the calculation (Table V) have been chosen as follows: for the openings connecting to the outside the situation is like that in experiment B. The coefficient $C_{v_{ij}}$ is determined so that the effective surface given by formula (28) corresponds to the experiment. For the case of the wide open door its coefficient is close to 1. The flow contraction in the openings was visualized with smoke giving a justification for this choice of the velocity coefficients.

Experiment C1 confirms that the effect of the door plays a minor role when the opening in series is relatively small. Experiments C2 and C3 are consistent with formula (30). In experiment C4 the areas in parallel are added and the door in series is of the same size as the sum of the two

TABLE V Experimental results for experiment C: two openings in series or in parallel

Experiment ⇒	C1	C2	C3	C4
S_i† [m²]	0.7	0.7	0.7	0.7 + 0.7
C_{v_i}	0.7	0.7	0.7	0.7
S_{ii}† [m²]	1.90	0.9	0.72	1.90
C_{v_i}	1	0.7	0.7	1
S_2 [m²]	1.78	1.78	1.78	1.78
C_{v_2}	0.7	0.7	0.7	0.7
H total [m]	6.45	6.45	6.45	6.45
Z_1 [m]	− 0.2	− 0.2	− 0.2	− 0.2
Z_2 [m]	7.15	7.15	7.15	6.45
T_i [°C]	18.9	19.2	19.2	19.2
T_e [°C]	9.1	9.1	9.1	9.1
Z_n‡ [m]	5.56	5.87	5.96	4.39
V_1 measured [m/s]	1.32	1.1	1.01	0.98
V_1 calculated ¶ [m/s]	1.39	1.14	1.04	1.08
Difference	5%	3%	3%	9%
V_2 measured [m/s]	0.72	0.64	0.64	1.0
V_2 calculated ¶ [m/s]	0.86	0.81	0.79	0.96
Difference	16%	21%	19%	− 4%
m_1§ [kg/s]	1.10	1.00	1,01	1.64
m_2§ mes [kg/s]	1.27	1.13	1.13	1.76
$m_2 - m_1$ (flow balance)	0.17	0.12	0.11	0.12

† Formula (35).
‡ Formula (36).
¶ Formula (37).
§ Calculation of S effective with formula (33).

windows. In conclusion, formula (30) is found valid for two openings in series, although the uncertainty in the discharge coefficients is still large.

4 CONCLUSION

Single sided ventilation has been investigated by several teams in different series of experiments using tracer gas techniques. One series of experiments used a short time tracer gas decay measurements in real buildings and in a test cell. Another series of longer experiments was carried out in a test cell using at the same time the constant tracer gas injection technique and a new heat balance approach. The latter method proved to be more accurate than the constant tracer gas injection.

Comparison of the experimentally derived air flows with theoretical predictions has verified that existing theoretical models are of limited applicability. New correlations have been derived from these experiments. From the first series of experiments, a Correction Factor is proposed to take account of the wind effect in configurations with single sided ventilation through large openings. The correlation was based on experiments characterized by strong and relatively steady wind and small temperature differences. It has been validated against experimental data with satisfactory results.

From the second series of experiments a physical multi-term model was derived, which accounts for both the thermal effect and the wind. A simple correlation model could be found in the case of constant wind, flowing parallel to the opening. The multi-term model improves considerably the agreement between the simulated air flow rates and the measured ones. It must be stressed, however, that the model is derived from a particular experimental condition and that e.g. the wind direction was dominantly 200° off the normal to the opening; this is certainly a limitation to the use of the model.

This remark also points towards the needs for further investigation: the limits of applicability of the presented models should be further explored and verified against other ranges of environmental conditions (wind speeds and directions, temperature differences), opening configurations and dimensions, as well as room layout.

Analysis of the data and comparison with simulation results has shown that existing air flow network simulation tools fail to predict the air flow accurately, in the case of single sided natural ventilation under conditions of medium and high temperature differences. This is due to the fact that network models do not account for the wind effect in the case of single sided ventilation. However, medium to high wind speeds and small indoor/outdoor temperature differences are a common characteristic in the case of naturally ventilated buildings in hot climates.

For cross ventilation the short review of models predicting air motion in naturally ventilated buildings shows very clearly the two different ways developed until now to solve this problem. Most of the studies have been devoted to the prediction of air flow rates. It is clear that this orientation has been given by a general energy conservation point of view, but as pointed out by Murakami [20], the fluid dynamics inside a cross ventilated building is very different from the one existing in an air infiltrated building and the models used to predict the air flow rates in this last case have to be carefully tested before using them in natural ventilation.

For the LESO building in Lausanne, the goal of the PASCOOL experiments was to verify whether, during summer ventilation, the air flow resistances formed by open doors in series can be predicted with a simple Bernoulli model and usual discharge coefficients.

The experiments carried out during the PASCOOL programme in different sites and with different experimental facilities confirm this theoretical analysis, and show how difficult it is to get a real information by classical measurement techniques in cross ventilation. There is a real need of specific research and specific experiments to solve this problem.

Future work is required to predict indoor air motion: effects of room geometry, partitioning, effects of external architecture of the building have to be studied carefully. In an other field, in order to increase indoor comfort conditions, the influence of turbulence intensity on human comfort in naturally ventilated environment has to be precised.

Acknowledgements

The present study was carried out within the framework of PASCOOL CEC Research Programme, which was partly financed by the Commission of the European Union, DG XII for Science, Research and Development.

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