

## INTEGRATION OF NATURAL VENTILATION MODELS IN THE HYGROTHERMAL AND ENERGY SIMULATION PROGRAM POWERDOMUS

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### ABSTRACT

The present study aims to validate several cross and single-sided natural ventilation models implemented in the Building Hygrothermal and Energy Simulation program PowerDomus (Mendes et al., 2003) i.e. the British Standard (1999) model for cross ventilation and the de Gids and Phaff's (1982) and Larsen's (2006) models for single-sided ventilation. Airflow rates obtained by those models are compared to the measurements performed in two full-scale buildings: one single room house located in a wind tunnel facility and one real three-storey building. Results show a large variation of airflow rates provided by the different models. Larsen's model coupled to the CPCALC algorithm has shown better results in comparison to both wind tunnel and on-site experiments.

### INTRODUCTION

Healthy indoor climate conditions and, at the same time, energy efficient and environmentally friendly building is a clear challenge. This is valid for existing buildings as well as for early-stage design processes. Creating better indoor air conditions to the occupants is certainly the main aspect when health and productivity are taken into account. Full air conditioned systems were in the past considered as the ultimate choice, but today a more balanced view is found in many countries and among many people (Van der Aa and 't Veld, 2004). Nowadays, the combination of natural ventilation and air conditioning systems are essential to reduce building energy consumption.

Natural ventilation can be classified according to two configurations: ventilation through a unique aperture (single-sided ventilation) and through multiple ones (cross ventilation). If the modeling of cross ventilation is currently well defined (British Standards, 1999), that of single-sided ventilation is widely discussed since early 80's because of the complexity for existing models to reproduce the airflow through just one aperture in a building zone. Differently from the cross-ventilation, in single-sided ventilation, the turbulence of the wind and variation in the pressure gradients induced by e.g. wind gusts strongly affect the airflow through an opening (Larsen, 2006). Since those parameters are unsteady,

the airflow in single-sided ventilation is much more difficult to evaluate.

In 1982, the first most relevant model to calculate natural single-sided ventilation in buildings was presented in de Gids and Phaff (1982). They proposed an approach to calculate the airflow in single-sided ventilation zones, where the air change resulting from opening a window in a room while maintaining the internal door closed was the subject of investigation. Measurements have been carried out in different locations, all located on the first floor of buildings situated in an urban environment and surrounded by buildings up to 4 floors high. They have then proposed an empirical expression to calculate the airflow through an opening based on the air velocity, temperature variation and the opening area.

Seventeen years after the presentation of the de Gids and Phaff model, the British Standards (British Standards, 1999) published formulae to calculate the airflow in a single-zone with just one opening. In 2005, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2005b) proposed another expression to calculate the airflow in a single-sided ventilation residential buildings. That expression was the first to take into account the wind incidence angle.

Finally, in 2006, based on de Gids and Phaff's model, Larsen (2006) concluded that a more precise design expression found from wind tunnel measurements can be used to predict airflows from single-sided ventilation. From Larsen's experimental work (2006), they noticed that the wind prevails on the windward side and that the temperature difference stands out on the leeward side of the building.

Recently, more advanced analysis to calculate the airflow through openings has been performed. Based on the evolution of computational hardware and on advances of CFD (Computational Fluid Dynamics) software, new methods to study the airflow in single-sided openings started to be developed (Papakonstantinou et al., 2000; Jiang et al., 2003). However, in the case of natural ventilation, the CFD approach requires the modeling of large computational domain and the use of high-order turbulence models such as Reynolds Stress Models (Emmel et al., 2007) in order to represent correctly

the airflow around the buildings. Consequently, the use of CFD is complex and time consuming so that empirical expressions are still widely used when whole building hygrothermal analysis are necessary.

The main idea of this paper is to validate the integration of the cross ventilation model proposed by the British Standard (1999) and to compare the prediction given by the single-sided ventilation models of Gids and Phaff (1982) and Larsen (2006) to results obtained from wind tunnel and on-site experiments. The model descriptions of the cross and single-sided ventilations are presented in the first two sections. The two methodologies for evaluating the wind pressure coefficient, that is necessary as an input parameter of the cross and single-sided ventilation models, are given in the third section. The fourth section presents the wind tunnel and on-site configuration. Results are presented and discussed in the last section.

### CROSS VENTILATION MODEL

According to the literature, the cross-ventilation is much simpler to calculate than single-sided ventilation. The flows induced by either thermal buoyancy, wind or a combination of them presented in the British Standards (1999) have been adopted to define the cross-ventilation airflow formulation employed here.

The airflows through more than one opening could be driven either by thermal buoyancy (if there are openings at different heights in the building) or by the wind. A general expression to calculate the pressure driven airflows (in  $m^3/s$ ) through openings due to thermal buoyancy is:

$$Q_V = C_D A_b \sqrt{\frac{2\Delta T g H}{T_M}} \quad (1)$$

where the discharge coefficient for window openings  $C_D$  is often within the range between 0.6 and 0.75 (an average value of 0.67 is used in the present study),  $\Delta T$  is the temperature difference between inside and outside (K),  $g$  is the gravity acceleration ( $m/s^2$ ),  $H$  is the vertical distance between the two openings (m),  $T_M$  is the mean temperature between the indoor and outdoor air and  $A_b$  is the total opening area (in  $m^2$ ) that can be calculated as presented in Eq. 2.

$$\frac{1}{A_b^2} = \frac{1}{\left(\sum_{n=1}^n A_n\right)^2} + \frac{1}{\left(\sum_{m=1}^m A_m\right)^2} \quad (2)$$

where  $n$  and  $m$  are the number of openings. If the indoor temperature is higher than the outdoor temperature, the  $n$ -openings will be the ones over the neutral plane level (where the heated air flows to outdoor) and the  $m$ -openings are the ones under the neutral plane level (where the cool air flows to indoor), see Figure 1. In cases where the indoor temperature is lower than the outdoor temperature,

than everything is the opposite. If one opening is sectioned by the neutral plane level, its area should be divided into the  $n$  and  $m$  opening sum.

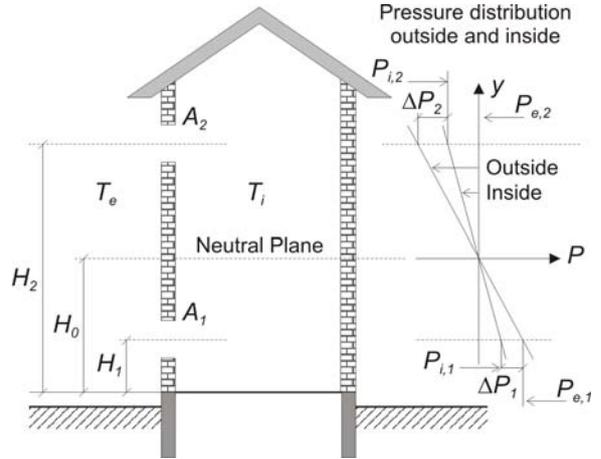


Figure 1. Pressure difference around the neutral plane in a building ventilated only by thermal buoyancy.

To calculate the airflow rate caused by wind in a cross-ventilation problem, the following equation should be used (British Standards, 1999):

$$Q_V = C_D A_w U(z = BH) \sqrt{|C_{P,1} - C_{P,2}|} \quad (3)$$

where  $A_w$  can be calculated by using Eq. 2 but, in these case, the  $n$ -openings are the openings with highest  $C_P$  (pressure coefficient) value, otherwise they are  $m$ -openings.  $U(z=BH)$  is the wind velocity at the building's height and  $C_{P,i=1,2}$  are the pressure coefficients that can be evaluated according to the expressions given in third section. The wind velocity at the building's height is calculated using Counihan's expression (Counihan, 1975):

$$\frac{U(z)}{U(10)} = \left(\frac{z}{10}\right)^\alpha \quad (4)$$

where  $\alpha$  depends on the terrain roughness (from 0.10 to 0.45).

Following the British Standards, if the inequation:

$$\frac{U(z = BH)}{\sqrt{\Delta T}} < 0.26 \sqrt{\frac{A_b}{A_w} \frac{H}{\Delta C_P}} \quad (5)$$

is satisfied, the airflow should be calculated through Eq. 1, in the other way, the Expression 3 should be used.

### SINGLE-SIDED VENTILATION MODELS

In the sequence, two models to calculate the airflow for single-sided ventilated environments are presented. The modeling procedure performed by de Gids and Phaff (1982) used measurements performed in a building located in an urban environment, while the model proposed by Larsen (2006) used data from

both wind tunnel and on-site experiments. The main difference is that the model of Larsen (2006) integrates the effect of wind incidence angle.

### de Gids and Phaff (1982)

From measurements, de Gids and Phaff found an expression which describes the flow rate (in  $m^3/s$ ) in a single-sided ventilated building (de Gids and Phaff, 1982):

$$Q_V = \frac{A}{2} \sqrt{C_1 U(10)^2 + C_2 h \Delta T + C_3} \quad (6)$$

where  $A$  is the opening area (in  $m^2$ ),  $h$  is the opening height (in  $m$ ),  $U(10)$  is the reference velocity at 10m high ( $m/s$ ) and  $\Delta T$  is the mean temperature difference between inside and outside ( $K$ ).

The coefficients of this model are (de Gids and Phaff, 1982): the dimensionless coefficient depending on the wind effect ( $C_1 = 0.001$ ), the buoyancy effect ( $C_2 = 0.0035$ ) and the wind turbulence effect ( $C_3 = 0.01$ ).

### Larsen (2006)

As a result of her experiments performed in 2006, Larsen proposed a new model (Larsen, 2006) to describe the airflow in single-sided ventilation which is presented in Eq. 7.

$$Q_V = A \sqrt{C_1 f(\beta) |C_p| U(z)^2 + C_2 h \Delta T + C_3 \frac{\Delta C_{P, opening} \Delta T^2}{U(z)}} \quad (7)$$

where  $C_p$  is the pressure coefficient which can be calculated by the methods presented in third section of this paper,  $U(z)$  is the air speed at the opening height,  $h$  is the opening height ( $m$ ), the constants  $C_1$ ,  $C_2$  and  $C_3$  are defined as presented in Table 1. If  $U(z)$  tends to zero, just the  $C_2$  term must be considered, assuring the consistency of the equation.

Table 1  
Constants  $C_1$ ,  $C_2$  and  $C_3$  (Larsen and Heiselberg, 2008)

Direction	Incidence Angle ( $\beta$ )	$C_1$	$C_2$	$C_3$
Windward	$0^\circ-75^\circ$ ; $285^\circ-360^\circ$	0.0015	0.0009	-0.0005
Leeward	$105^\circ-255^\circ$	0.0050	0.0009	0.0160
Parallel	$90^\circ$ or $270^\circ$	0.0010	0.0005	0.0111

where  $\beta$  is the wind incidence angle ( $^\circ$ ) and  $\Delta C_{P, opening}$  and  $f(\beta)$  are calculated from:

$$\Delta C_{P, opening} = 9.1894^{-9} \beta^3 - 2.62610^{-6} \beta^2 - 0.0002354 \beta + 0.113 \quad (8)$$

$$f(\beta) = -3.284312 \times 10^{-9} \beta^4 + 2.363134 \times 10^{-6} \beta^3 - 5.24549 \times 10^{-4} \beta^2 + 3.581077 \times 10^{-2} \beta + 0.3017574 \quad (9)$$

It is also seen that the value of the constants  $C_1$ ,  $C_2$  and  $C_3$  depends on the wind direction. This is due to

the fact that the flows in the three cases (windward, leeward and parallel) are very different one from each other and therefore also have different weighting of the terms including wind pressure, thermal forces and fluctuating forces. Contrary to what was expected,  $C_1$  does not have the largest weight factor at windward side, but it remains the most dominating factor in this case. In the case where the opening is on the leeward side of the building the fluctuating term prevails. This is also the case in the parallel wind situations, but here the difference is not as high as in the leeward case.

## PRESSURE COEFFICIENT CALCULATION

The pressure created by the wind on the building is described in Eq. 10. It is calculated by multiplying a dimensionless pressure coefficient  $C_p$  with the dynamic pressure.

$$P_{wind} = C_p \frac{1}{2} \rho_e U(z)^2 \quad (10)$$

where  $U(z)$  is calculated by Eq. 4. The  $C_p$  coefficient is determined by the shape of the building, the wind direction and the surrounding terrain. In the sequence, two models to calculate the distribution of  $C_p$  have been presented. The first one considers an unique value for the whole surface whereas the second one calculates the  $C_p$  value at any location on the surface.

### Mean $C_p$ Calculation

According to (ASHRAE, 2005a), the distribution of  $C_p$  on a low-rise building associated to the variation of the incidence angle can be estimated through the curve presented in Figure 2. According to Deru and Burns (2003), there are several correlations for the wind pressure coefficient derived from wind tunnel experimental data in order of increasing complexity and accuracy, as those proposed by (Walton, 1982), (Swami and Chandra, 1988), and the COMIS group (Feustel and Rayner-Hooson, 1990). These correlations are potentially inaccurate in situations that introduce turbulence to the flow; for example: high terrain roughness or local shielding, irregular shaped buildings (nonrectangular or rectangular with aspect ratios far from a cube) or buildings with overhangs or fins. The model developed by Swami and Chandra (1988) was selected as the best fit for the needs of this work:

$$C_p = C_p(\beta = 0) \times \ln \left[ 1.248 - 0.703 \sin \frac{\beta}{2} - 1.175 \sin^2 \beta + 0.131 \sin^3 \left( 2\beta \frac{L_1}{L_2} \right) + 0.769 \cos \frac{\beta}{2} + 0.717 \cos^2 \frac{\beta}{2} \right] \quad (11)$$

This expression calculates the surface pressure coefficient normalized to the pressure coefficient at zero incidence angle as a function of the wind incidence angle ( $\beta$ ) within a  $[0^\circ, 180^\circ]$  domain, where

values higher than  $180^\circ$  are obtained by symmetry, and the natural logarithm of the side ratio (ratio of the lengths of adjacent walls  $L_1$  and  $L_2$ ). For vertical walls, Swami and Chandra (1988) recommended using a value of 0.6 for the pressure coefficient at zero incidence. Note that the values obtained by Eq. 11 lie in Figure 2 gray area.

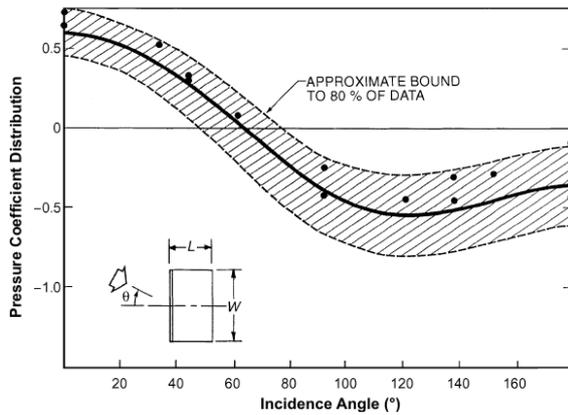


Figure 2. Variation of surface-averaged wall pressure coefficients for low-rise buildings (ASHRAE, 2005a).

### CPCALC Model

Considered the main algorithm of CPCALC+ (software for calculating wind pressure coefficients on the envelope of a building which has been used for airflow modeling), the idea of the CPCALC algorithm initiated within the European Research Programme PASCOOL (Passive Cooling of Buildings) of the Commission of the European Communities, Directorate General for Energy (Grosso, 1993; Grosso et al., 1994). In 1992 it was developed at the Lawrence Berkeley Laboratory (Feustel and Rayner-Hooson, 1990; Grosso, 1992) within the COMIS workshop on infiltration and ventilation, and being upgraded within the IEA-ANNEX 23 on multizone airflow modeling (IEA, 1996).

CPCALC and CPCALC+ were developed in order to fulfill the requirements of multizone airflow models which need a detailed evaluation of the wind pressure distribution around buildings. Scientists and professionals using this program, and who do not have the possibility to test a scale model of their building in a wind tunnel, do not need to extrapolate  $C_p$  data from tables usually yielding wall-averaged  $C_p$  values (Liddament, 1986).

The CPCALC model uses the following input variables:  $\beta$  wind incidence angle ( $^\circ$ ),  $\alpha$ : wind velocity profile (Counihan, 1975),  $sbh$ : surround building height (m),  $pad$ : plan area density (%), building height (m), wall azimuth (m) the coordinates  $x$  and  $y$  of the middle of the opening related to the origin of the building (m) and the frontal and side aspect ratios of the building (m).

Based on these input data, the CPCALC algorithm is able to calculate the pressure coefficient value at any

point on building's surface, in this case, at the center of the opening.

## EXPERIMENTS

In this section the experiments which have been chosen to analyse and compare the cross and single-sided ventilation models showed in the previous section are presented. The wind tunnel experiment presents results for both cross and single-sided ventilation whereas the on-site one is dedicated to the validation of the single-sided ventilation model.

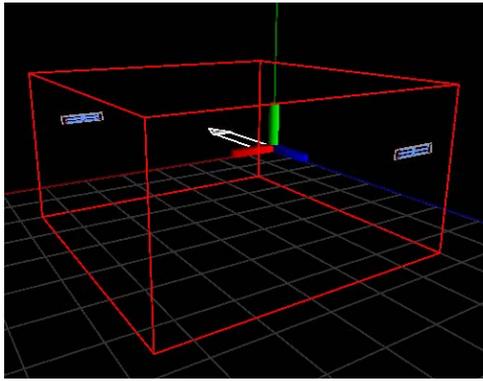
### Wind Tunnel Experiment

The wind tunnel experiment has been carried out in a full-scale wind tunnel at the Japanese Building Research institute (BRI) by Larsen (2006) to investigate the airflow through openings in cross and single-sided ventilation situations. The building's dimension were  $5.56m \times 5.56m \times 3.00m$ , which means that scale effects were avoided. The opening's width and height were  $0.86m \times 0.15m$  for both windows in the cross-ventilation case, they were positioned  $0.54m$  away from the right edge and  $0.925m$  from the top (see Figure 3 (a)). For the single-sided case, the openings dimensions were  $0.86m \times 1.40m$  of width and height, respectively. In this case, it was positioned at  $0.54m$  away from the right edge and  $0.69m$  away from the top of the building (see Figure 3 (b)). The internal room height was  $2.4m$  and the thickness of the walls was  $0.10m$ . The room volume was  $68.95m^3$ .

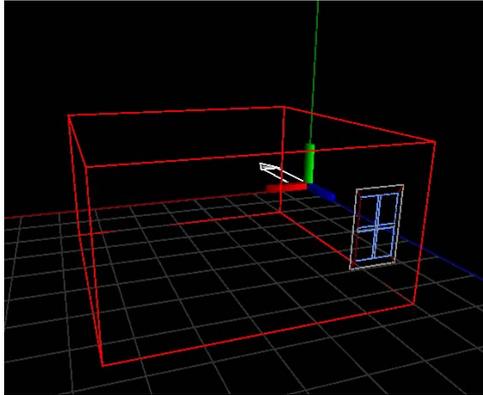
The experiment consisted in varying the wind speed in the tunnel (1, 3 and  $5m/s$ ) with a turbulence intensity less than 5% while imposing distinct temperature differences of 0, 5 and  $10K$  between the internal and external air. The wind speed profile created in this wind tunnel was almost uniform, which resulted in a wind profile that differs from outdoor conditions as it was not able to reproduce the atmospheric boundary layer. The buildings was also rotated between  $0^\circ$  and  $345^\circ$  with either a  $15^\circ$  or a  $30^\circ$  increase to get measurements for different angles of the wind. A total of 159 different cases were studied. The air-change rate was measured with the tracer gas decay method.

### On-Site Experiment

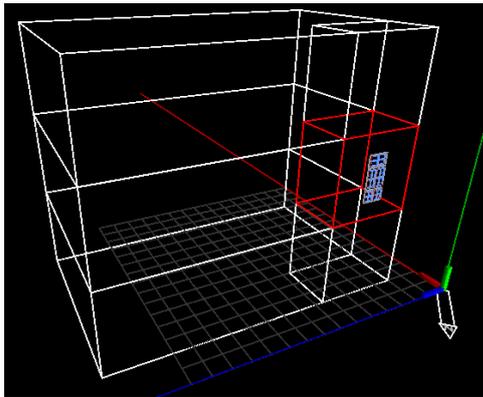
The building selected for the on-site experiment is the Institute of Meteorology and Physics of the Atmospheric Environment, which is a three-storey, naturally ventilated, office building referred as the NOA (National Observatory of Athens) building in the sequence. Each floor is about  $4.50m$  high and the dimensions are  $10.20m \times 16.30m$  of length and width respectively. Ventilation experiments were held on the first floor (IEA, 1996). The selected office room (zone in red in Figure 3 (c)) was isolated from the rest of the building. The room has a  $13.59m^2$  floor area, while its length is equal to  $3.00m$ .



(a)



(b)



(c)

Figure 3. Experiments designs performed into the PowerDomus software: (a) and (b) wind tunnel for cross and single-sided cases; (c) NOA building (single-sided case).

The only external window is on the west wall and is divided in five parts, A1, A2, B1, B2 and C, which can open separately, providing the possibility to vary the opening area (Figure 4) by opening different parts. The total window area is  $2.50m^2$  and its angle to the North is  $315^\circ$ .

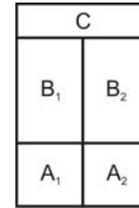


Figure 4. Window parts of the NOA Building.

Dimensions and area of each part of the opening are presented in (Dascalaki et al., 1999). Airflow rates across the openings have been performed according to the single tracer gas decay technique. Fourteen different experiments have been taken into account. The mean climatic conditions for each experiment are given in Table 2.

Table 2

Opening configuration and mean climatic conditions for single-sided ventilation experiments in the NOA building.

Experiment	$T_I$	$T_O$	$U(10)$	$\beta$
$A_1 + A_2$	31.4	31.3	6.8	40
$B_1 + B_2$	31.8	32.6	3.0	70
C	32.1	30.6	5.0	30
$A_2 + B_2$	31.5	32.5	6.7	50
$A_1 + A_2 + B_1 + B_2$	31.5	30.5	1.7	50
$B_1 + B_2 + C$	29.2	28.8	1.6	45
All	31.0	30.2	3.6	12
$A_2 + C$	31.7	31.2	5.4	30
$B_2 + C$	31.8	30.7	4.9	70
$A_1 + A_2 + C$	31.0	30.8	4.2	50
$A_1 + B_1 + C$	28.8	27.6	2.0	35
$A_2 + B_2 + C$	31.6	30.1	5.0	20
$A_1 + A_2 + B_1 + C$	31.0	29.6	3.1	35
$A_1 + A_2 + B_2 + C$	31.0	28.2	3.4	37

where  $T_I$  is the indoor temperature ( $^\circ C$ );  $T_O$  is the outdoor temperature ( $^\circ C$ ),  $U_{10}$  is the wind velocity at 10m high (m/s) and  $\beta$  is the wind incidence angle ( $^\circ$ ).

## RESULTS

This section presents the comparisons between the results obtained by using the PowerDomus software and the experimental data obtained for both wind tunnel and on-site experiments.

### Wind Tunnel Simulation

#### Cross Ventilation

Figure 5 presents the results of wind tunnel cross ventilation experiments of Larsen (2006) and the predictions of the British Standard (1999) implemented in the PowerDomus software.

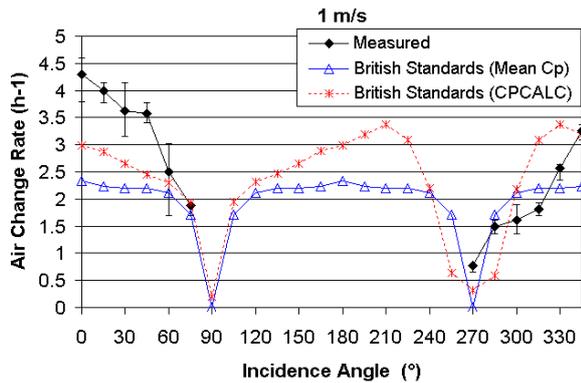


Figure 5. Comparisons between the experimental and simulation results performed for the wind tunnel – cross ventilation case.

Among the six different experiments (three different wind velocities and three distinct temperature differences between the indoor air and the outdoor one) performed by Larsen (2006), only one is presented here (wind velocity of 1m/s, isothermal case). In fact, as shown by Eq. 3, the airflow rate is a linear function of the wind velocity so that results for other velocities can easily be interpolated from the presented ones. The experimental results clearly showed the linear tendency. Moreover, because of the fact that the openings are located at the same height, there is no thermal buoyancy effect, in this way the negligible air change rate variations caused by temperature differences has not been treated in this case with high wind velocities. Results obtained by the model are the same for distinct temperature differences in the present configuration. The experimental results showed also that tendency with a slight variation probably due to the precision of the experimental measurements. The experimental results presented in Figure 5 are the airflow rate averages obtained from three distinct temperature differences results.

Results show that the British Standard (Mean  $C_p$ ) model is not capable of predicting the variation of the airflow according to the wind direction. The British Standard (CPCALC) model tends to better follow this variation. One particular drawback of the Mean  $C_p$ -based model occurs when the wind is parallel to the openings. In this case, this model predicts no flow (the  $C_p$  difference between the openings is null) whereas the CPCALC-based model is able to detect a small but notable airflow.

However, it can be seen that the two models present almost the same mean relative difference of about 30% considering the whole set of data (Table 3).

Table 3  
Relative differences (%) for the wind tunnel experiment – cross ventilation case.

Model	Relative Differences (%)
Mean $C_p$ (A)	32.46
CPCALC (A)	31.11

### Single-Sided Ventilation

In order to illustrate the behavior of each single-sided ventilation model and to analyse the effect from different wind speeds (1, 3 and 5m/s), temperature differences (0, 5 and 10°C) and incidence angles (varying from 0 to 345°) on the airflow, 27 simulations using the PowerDomus software have been performed.

As simulation parameters, for the pressure coefficient calculation through the Mean  $C_p$  method an  $\alpha = 0.10$  has been adopted, which is the value when there are no obstructions affecting the wind. For the CPCALC method the same  $\alpha = 0.10$  has been used and for the plan area density and surrounding building height the values of  $pad = sbh = 0$ , have been adopted because there are no obstructions inside the wind tunnel.

The results, presented in Figure 6, represents the air-change rates as a function of the incidence angle and the temperature difference of 5°C. Each graphic represents one of the selected wind speeds. On the other hand, Larsen's model does present the expected angular dependency. For the lower wind velocity, wind and temperature gradient effects are about the same so that the third term of Eq. 6 really affects the results. In particular, the influence of the non symmetrical term  $\Delta C_p$  is visible for the incidence angle in  $120^\circ \leq \beta \leq 240^\circ$ . For higher wind velocity, the first term of Eq. 6, and  $f(\beta)$  term, predominates so that the obtained air change rate becomes more symmetrical, at least when the Mean  $C_p$  method is used.

Analysing the results for the de Gids and Phaff model, it is noticed that there are no variations on the air change rates when the incidence angle changes. This happens because the model does not take into account the incidence angle in its calculation. In this way, a constant single value is obtained for each wind speed.

The differences noticed between the Larsen (Mean  $C_p$ ) and Larsen (CPCALC) models are caused by the calculation of the pressure coefficient. While the Mean  $C_p$  method calculates the wall mean pressure coefficient, the CPCALC method estimates the  $C_p$  value for the geometric center of the opening. As a consequence, the  $C_p$  values calculated by the CPCALC method are higher when the wind incidents directly on the window (angle in the interval of  $270^\circ \leq \beta \leq 360^\circ$ ) than for angles between  $0^\circ \leq \beta \leq 90^\circ$ . The Mean  $C_p$  method is not able to represent this actual behavior.

The relative differences for the windward, leeward and parallel incidence angles have been presented in Table 4. It is noticed for the windward and leeward incidence angles, the Larsen's model by using the CPCALC calculation presents slightly better results than the two others. When the parallel incidence angle is analysed, it is noticed that the Mean  $C_p$  method has a difference higher than the others. This

represents the model difficulty in calculates the pressure coefficient in angles near 90°.

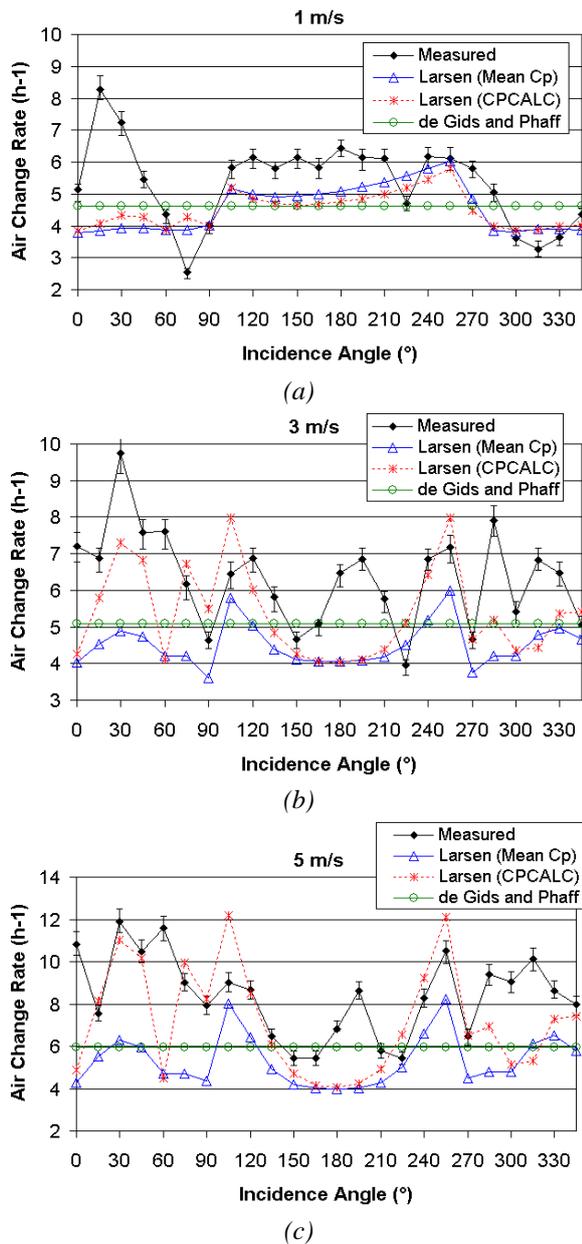


Figure 6. Comparisons between the experimental and simulation results performed into the PowerDomus software for the wind tunnel case with wind speeds of: (a) 1, (b) 3 and (c) 5 m/s – single-sided ventilation case.

Table 4

Relative differences (%) for the wind tunnel experiment – single-sided ventilation case.

Model	Windward	Leeward	Parallel
Larsen (Mean $C_p$ )	34.25	20.85	22.38
Larsen (CPCALC)	24.99	19.75	7.68
de Gids and Phaff	29.89	20.39	14.68

### On-Site Simulation

The comparisons of the on-site experiment and the simulations performed by PowerDomus are compared in this section. According to (Dascalaki et

al., 1999), the building is located in an open urban environment on top of a hill across from the Acropolis of Athens, consequently, the simulation parameter  $\alpha = 0.28$  has been chosen for the pressure coefficient calculation by the Mean  $C_p$  and by the CPCALC methods. For the last one, the  $pad = sbh = 0$  have also been used. Figure 7 shows the comparisons between the simulation and the measured results.

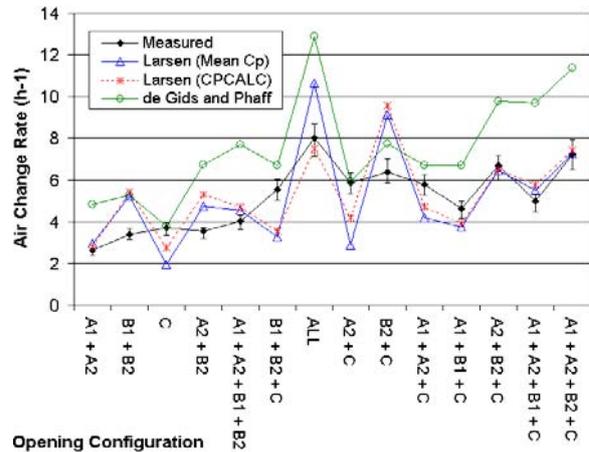


Figure 7. Comparisons between the experimental and simulation results performed into the PowerDomus software for the NOA Building case.

According to the results presented in Figure 7, it has been noticed that the Larsen model using the CPCALC method to calculate the pressure coefficient has provided the best results. When the relative differences for all the obtained results are calculated, the graphical analysis is verified (Table 5).

Table 5

Relative differences for the NOA Building experiment.

Model	Relative Differences (%)
Larsen (Mean $C_p$ )	27.71
Larsen (CPCALC)	24.03
de Gids and Phaff	49.06

It should be noticed that the wind incidence angle stayed around 90° during the experiments for which Larsen model already showed better prediction in the wind tunnel experiment. The slightly better results of Larsen (CPCALC) compared to Mean  $C_p$  essentially occur for 3 points (C, All, A<sub>2</sub> + C) where the angle is about 70° for which this model showed better prediction too on the wind tunnel experiment. In the other side, the de Gids and Phaff model, which presented great results for the wind tunnel experiment, was not capable to provide good results in this case.

### CONCLUSIONS

Several cross and single-sided natural ventilation simulations through openings were performed in the building hygrothermal and energy simulation software PowerDomus. The simulations have been

compared to the experimental results carried out in a full-scale wind tunnel and in an on-site three storey office building.

Results showed that the use of the CPCALC algorithm actually improves the predictions, particularly in the case of single-sided configurations.

It has also been found that the current state-of-the-art empirical models for natural ventilation are capable of predicting the actual trends. However, the predictions still present a high difference of about 30%. More accurate empirical models are still needed to evaluate the air change rate by cross and single-sided natural ventilation.

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