COMPARATIVE ANALYSIS OF NATURAL SINGLE-SIDED VENTILATION MODELS FOR BUILDING SIMULATION

Roberto Zanetti Freire, roberto.freire@pucpr.br
Marc Olivier Abadie, marc.abadie@pucpr.br
Nathan Mendes, nathan.mendes@pucpr.br
Thermal System Laboratory - LST
Pontifical Catholic University of Paraná - PUCPR

Gustavo Henrique da Costa Oliveira, gustavo.oliveira@pucpr.br
Industrial and Systems Engineering Graduate Program - PPGEPS
Pontifical Catholic University of Paraná - PUCPR
Rua Imaculada Conceição, 1155. Curitiba/PR/Brazil - Zip Code 80215-901

Abstract. *Over the last decades, great efforts to reduce energy consumption in buildings have been performed. Due to the increase of the energy demand induced by the world demographic growth and the reduction of natural energy resources, new strategies to optimize HVAC energy consumption have been attracting attention of academic and industrial researchers. As a result, hybrid system capable of determining when passive strategies, such as natural ventilation per large apertures, can be used to reduce energy consumption of air-conditioning systems seems to be a valuable solution to reduce energy waste. Based on these concepts, two single-sided ventilation models aiming to determine the airflow rate through opened windows and doors have been evaluated in this paper: the de Gids and Phaff's original model (1982) and its enhanced version proposed by Larsen (2008) to account for wind direction. In the first part of this work, those natural ventilation models that have been implemented into a building hygrothermal and energy simulation software are presented. In a second part, the airflow rate predictions obtained by those models are compared to the measurements performed in two full-scale buildings. The first one is a* $5.56\ m \times 5.56\ m \times 3.00\ m$ *room located in the wind tunnel facility of the Japanese Building Research institute. The second one is a room located in the three-storey naturally-ventilated building of the Institute of Meteorology and Physics of the Atmospheric Environment in Athens, Greece. In those two experimental studies, all data needed to the models, such as wind velocity and direction, indoor and outdoor air temperature and airflow through the windows are available. Results show a large variation of airflow rates provided by the different models. Larsen's model coupled to the CPCALC algorithm to calculate the pressure coefficient in the center of the window has shown better results in comparison to the experimental for both wind tunnel and on-site experiments.*

Keywords: *Single-Sided Natural Ventilation, Wind Tunnel, Building Simulation, Airflow*

1. INTRODUCTION

Associated to thermal comfort and indoor air quality concepts, energy consumption is another important issue related to HVAC systems performance. Energy efficiency in buildings is nowadays an important issue due to the growth of energy costs, energy consumption and environmental impacts, especially those related to global warming.

In most developed countries, ventilation in buildings is today considered as an essential aspect in each building project where energy can easily wasted. Whereas in the past, the primary purpose of ventilation was to provide acceptable indoor air quality - and thus being viewed as energy loss, nowadays there is a growing interest in ventilation as part of an energy efficient strategy for achieving thermal comfort in summer. In the developed economies, buildings usually account for half of the fossil fuel consumed, so they must be designed or adapted to reduce energy consumption by a very large ratio (Fordham, 2000). Based on this concepts, the reduction of building energy consumption became a necessity. For that reason, one way to reduce energy consumption of commercial and residential buildings is the use of natural resources as natural ventilation to decrease (or increase) indoor temperature and relative humidity in order to provide acceptable indoor air conditions to the occupants.

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 process. 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. In fact, building air renewal can be achieved by either using natural driving forces or mechanically driven systems, but through natural strategies it is possible to reduce energy waste.

As a part of natural ventilation study, single-sided ventilation are 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 and Heiselberg, 2008). Since these 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). de Gids and Phaff 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 a formulae to calculate the airflow in a single-zone with just one opening. In 2005, According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2005b), another expression to calculate the airflow in a single-sided ventilation residential building was proposed. The expression proposed by ASHRAE was the first to take into account the wind incidence angle.

Finally, in 2006, based on Gids and Phaff's model, Larsen (Larsen and Heiselberg, 2008) concluded that a more precise design expression found from wind tunnel measurements can be used to predict airflows in single-sided ventilation in outdoors buildings. From his experimental results, Larsen noticed that the wind prevails on the windward side and that the temperature difference stands out on the leeward side of the buildings.

Recently, more advanced analysis to calculate the airflow through openings have 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, CFD methods are usually complex and time consuming, and nowadays expressions like the ones proposed by Gids and Phaff and by Larsen are still widely used when whole building hygrothermal analyzes are necessary.

The main idea of this paper is to compare the single-sided ventilation models proposed by Gids and Phaff and by Larsen to results obtained from wind tunnel and on-site experiments, in order to analyze the potential benefits brought by Larsen's model. Both models are presented in Section 2 of this paper. To calculate the airflow through a single opening using the model proposed by Larsen, the wind pressure coefficient (C_P) is necessary as an input parameter. In this way, its calculation using two methods are given in Section 3. In order to evaluate the precision of the prediction given by the two single-sided natural ventilation models presented in this work, Section 4 presents the two experimental configurations. Finally, analyzes and comparisons of the models are emphasized and, in the sequence, the conclusions are addressed.

2. 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 used measurements performed in a building located in an urban environment, while the model proposed by Larsen used data from wind tunnel and also from on-site experiments. The main difference is that the model of Larsen integrate the effect of wind incidence angle.

2.1 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):

$$Q_V = \frac{A}{2}\sqrt{C_1\,U_{10}^2 + C_2\,H\,\Delta T + C_3} \tag{1}$$

where A is the opening area (in m^2), H is the opening height (in m), U_{10} is the reference velocity at 10 meter height (m/s) and ΔT 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 ($C_3 = 0.01$).

2.2 Larsen (2008)

As a result of her experiments, Larsen proposed a new model to describe the airflow in single-sided ventilation which is presented in Eq. 2 (Larsen and Heiselberg, 2008).

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

where C_P is the pressure coefficient which can be calculated by the methods presented in Section 3 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 Tab. 1.

Table 1. Constants C_1, C_2 and C_3 [Larsen and Heiselberg, 2008].

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

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

$$\Delta C_{P,opening} = 9.1894\, 10^{-9}\beta^3 - 2.626\, 10^{-6}\beta^2 - 0.0002354\beta + 0.113 \tag{3}$$

$$f(\beta) = -3 \times 10^{-9}\beta^4 + 2 \times 10^{-6}\beta^3 - 5 \times 10^{-4}\beta^2 + 3.58 \times 10^{-2}\beta + 0.3018 \tag{4}$$

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 in 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.

3. PRESSURE COEFFICIENT CALCULATION

When natural ventilation is driven only by wind, the pressure difference depends on the wind velocity and direction. For example, for normal wind incidence angle, the wind will create an overpressure at the windward side of the building and an underpressure at the leeward side and the parallel sides of the building. The pressure created by the wind on the building is described in Eq. 5. It is calculated by multiplying a dimensionless pressure coefficient (C_P) with the dynamic pressure.

$$P_{wind} = C_P\, \frac{1}{2}\, \rho_e\, U(z)^2 \tag{5}$$

where $U(z)$ is calculated through Counihan's expression (Counihan, 1975):

$$\frac{U(z)}{U(10)} = \left(\frac{z}{z_{10}}\right)^{\alpha} \tag{6}$$

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.

3.1 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 Fig. 1.

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 was selected as the best fit for the needs of this work:

$$C_P = C_P(\beta = 0)\, ln \left[\begin{array}{l} 1.248 - 0.703\, sin\dfrac{\beta}{2} - 1.175\, sin^2\beta + 0.131\, sin^3(2\beta G) + \\ 0.769\, cos\dfrac{\beta}{2} + 0.07G^2\, sin^2\dfrac{\beta}{2} + 0.717\, cos^2\dfrac{\beta}{2} \end{array} \right] \tag{7}$$

where G is:

$$G = ln\left(\frac{L_1}{L_2}\right) \tag{8}$$

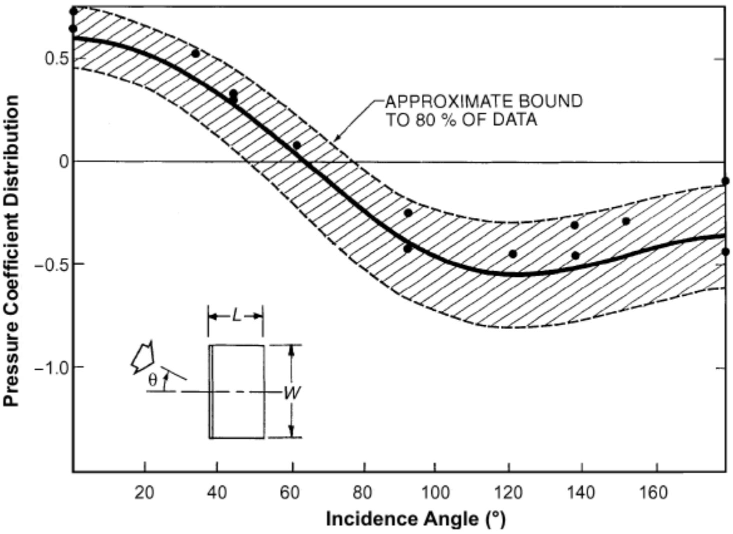

Figure 1. Variation of surface-averaged wall pressure coefficients for low-rise buildings [ASHRAE, 2005].

Table 2. Reference values for the wind velocity profile exponent (α).

Terrain Roughness Type	α
Level surfaces, surfaces of water basins, grass land	0.10
Flat open country with few, very small, and scattered obstructions	0.14
Rolling or level surfaces broken by numerous obstructions such as trees or small houses	0.22
Heterogeneous surface with obstacles larger than one story	0.28
Low density suburban areas	0.34
Medium-high density urban areas	0.40
Very high density inner city areas	0.45

This expression calculates the surface pressure coefficient normalized to the pressure coefficient at zero incidence angle as a function of the wind incidence angle (β) 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 recommend using a value of 0.6 for the pressure coefficient at zero incidence. Note that the values obtained with Eq. 7 lie in Fig. 1 gray area.

3.2 CPCALC Model

CPCALC+ is a program for calculating wind pressure coefficients on the envelope of a building for airflow modeling, developed 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). It has been 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).

Based on the necessity of calculating the pressure coefficients in the single-sided ventilation model developed by Larsen (Larsen and Heiselberg, 2008), which needs C_P values as input.

The CPCALC model uses the following input variables: β wind incidence angle (^{o}), α: wind velocity profile (see Tab. 2), 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.

4. EXPERIMENTS

In this section the experiments which have been chosen to analyze and compare the two single-sided ventilation models presented in Section 2 are presented. The idea is to compare the models by using two distinct situations: *i*) wind tunnel experiment, *ii*) on-site experiment. Such different experiments have been chosen because of the knowledge that most of the models developed based on wind tunnel experiments are not able to estimate the airflow in on-site single-sided ventilated buildings with good precision. In this way, comparisons analyzing results of wind tunnel and on-site experiments are considered essentials to test such models.

4.1 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 (Larsen and Heiselberg, 2008) to investigate the airflow through an opening in single-sided ventilation with the aim of finding a new design expression for this type of ventilation. The building's dimension were $5.56\ m \times 5.56\ m \times 3.00\ m$, which means that scale effects were avoided. The opening's width and height were $0.86\ m \times 1.40\ m$ respectively, and positioned $0.54\,m$ away from the right edge of the building. The internal room height was $2.4\,m$ and the thickness of the walls was $0.10\ m$. The room volume was $68.95\ m^3$.

The experiment consisted in varying the wind speed in the tunnel (1, 3 and $5\,m/s$) with a turbulence intensity less than 5% while imposing a temperature difference of 0, 5 and $10\,K$ 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^o and 345^o with either a 15^o or a 30^o 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.

The building was designed into the PowerDomus program in order to simulate the wind tunnel experiment. Because of the constant conditions as wind speed, wind incident angle and indoor and outdoor temperatures, specific weather files have been developed in order to reproduce the experiment conditions. The building structure designed into PowerDomus is presented in Fig. 2 (a).

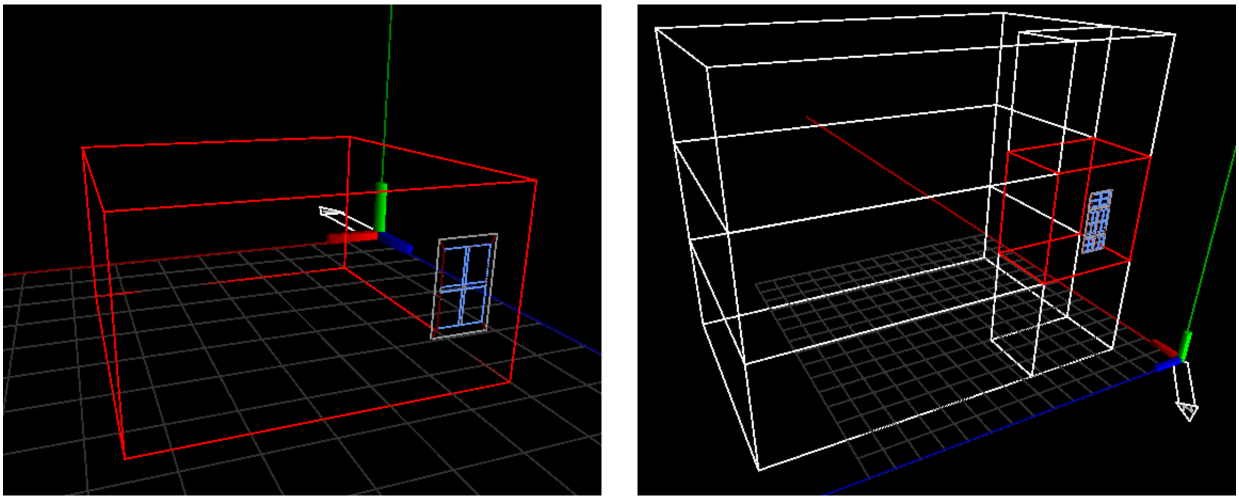
(a) (b)

Figure 2. Experiments designs performed into the PowerDomus software: (a) wind tunnel; (b) NOA building.

4.2 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 $4.50\ m$ high and the dimensions are $10.20\ m \times 16.30\ m$ of length and width respectively. Ventilation experiments were held on the first floor (IEA, 1996). The selected office room (zone in red in Fig. 2 (b)) was isolated from the rest of the building. The room has a $13.59\,m^2$ floor area, while its length is equal to $3.00\ m$. The only external window is on the west wall and is divided in five parts, A_l, A_2, B_1, B_2 and C, which can open separately, providing the possibility to vary the opening area (Fig. 3) by opening different parts. The total window area is $2.50\ m^2$ and its angle to the North is 315^o. The dimensions and area of each part of the opening are presented in Tab. 3.

In Fig. 2 (b) it is noticed that the building has just two zones per floor. This configuration has been justified by the single-sided ventilation models analyzed in this work, where the input variables that are necessary for the models calculation procedures are just related to the outdoor building geometry and to the zone where the opening is placed. In this way, the indoor zones geometric configuration are not important to the single-sided ventilation study presented here.

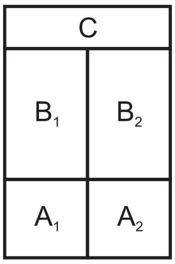

Figure 3. Window Parts of the NOA Building.

Table 3. Window dimensions of the NOA building.

Window Part	Height (m)	Width (m)	Opening Area (m^2)
A_1	0.65	0.53	0.34
A_2	0.65	0.53	0.34
B_1	1.13	1.13	0.60
B_2	1.13	1.13	0.60
C	062	1.06	0.66

The thermal behavior of the room, where the ventilation experiments took place, has been constantly monitored. Temperature on all internal and external surfaces have been monitored and the indoor air temperature has been measured at different heights: $0.3\,m$, $1.1\,m$ and $2.0\,m$ from the floor. Ambient air temperature data have been provided by standard meteorological stations located very close to the monitored room, as well as from a protected sensor located outside the opening. Wind speed and direction have been measured at heights of $10\ m$ and $18\ m$ at a very close distance from the window. Also, wind speed measurements were taken at the bottom of the opening. Finally, ventilation measurements were performed according to the single tracer gas decay technique. Fourteen different experiments have been taken into account. The opening area as well as the mean climatic conditions for each experiment are given in Table 4.

Table 4. Opening configuration and mean climatic conditions for single-sided ventilation experiments in the NOA building.

Experiment	Indoor Temperature (^oC)	Outdoor Temperature (^oC)	Wind Velocity (m/s)	Wind Direction Angle (^{o})
$A_1 + A_2$	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
$A_2 + B_2$	31.8	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

5. 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. In the sequence, simulation parameters are addressed and results of each simulation cases are discussed.

5.1 Wind Tunnel Simulation

In order to illustrate the behavior of each single-sided ventilation model and to analyze the effect from different wind speeds ($v = 1, 3$ and $5\ m/s$), temperature differences ($\Delta T = 0, 5$ and 10^oC) and incidence angles (varying from 0 to 345^o) 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 Fig. 4, represents the air-change rates as a function of the incidence angle and the temperature difference of $5^\circ C$. 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. 2 really affects the results. In particular, the influence of the non symmetrical term ΔC_P is visible for the incidence angle in $120^o \leq \theta \leq 240^o$. For higher wind velocity, the first term of Eq. 2, 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.

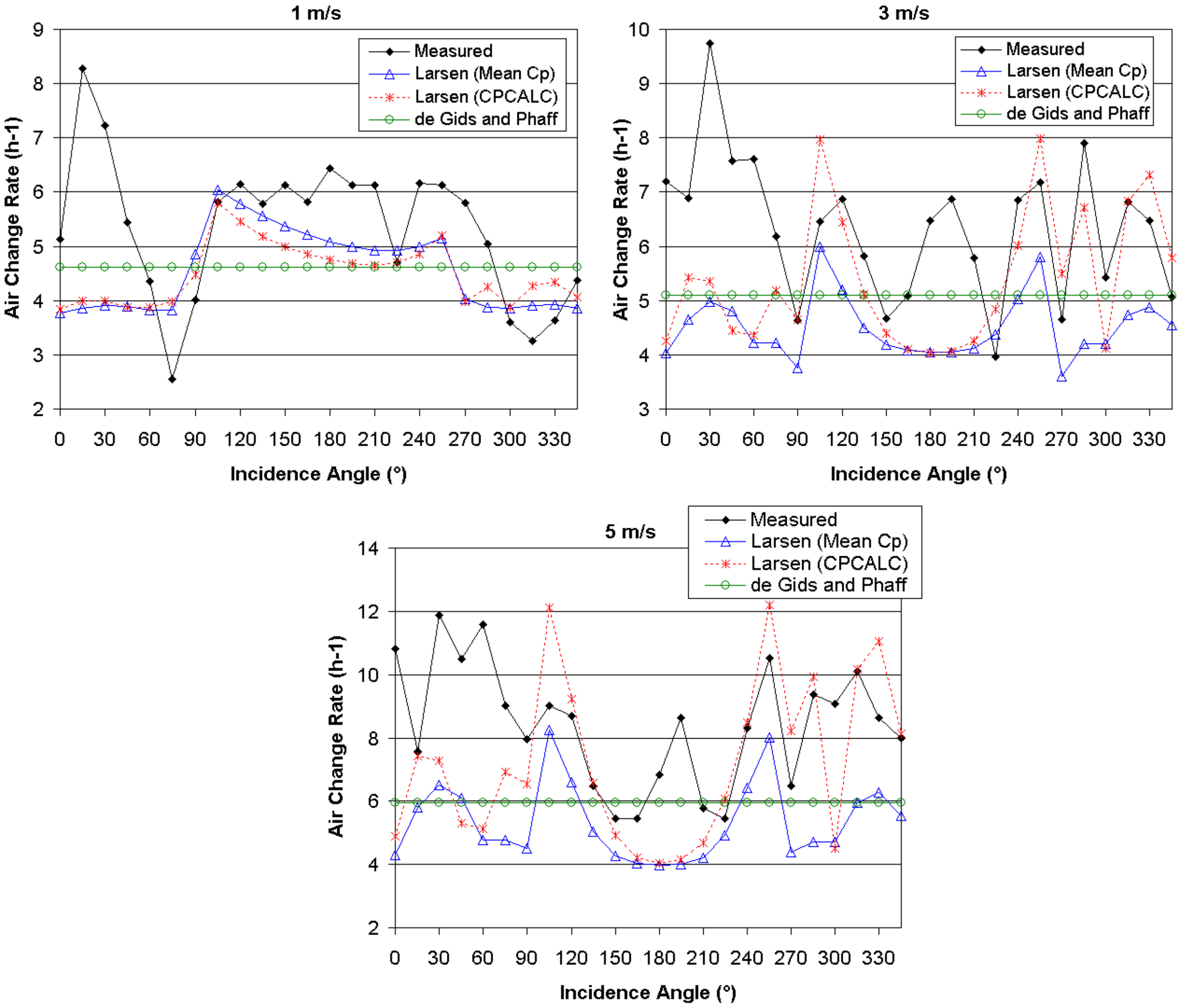

Figure 4. Comparisons between the experimental and simulation results performed into the PowerDomus software for the wind tunnel case with wind speeds of 1, 3 and 5 m/s.

Analyzing 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 $270^o \leq \theta \leq 360^o$) than for angles between $0^o \leq \theta \leq 90^o$. The Mean C_P method is nit able to represent this actual behavior.

The relative errors for the windward, leeward and parallel incidence angles have been presented in Tab. 5. 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 analyzed, it is noticed that the Mean C_P method has an error higher than the others. This represents the model difficulty in calculates the pressure coefficient in angles near 90^o.

Table 5. Relative errors (%) for the wind tunnel experiment.

Model	Windward	Leeward	Parallel
Larsen (Mean C_P)	34.35	20.12	28.25
Larsen (CPCALC)	26.75	18.19	17.64
de Gids and Phaff	29.89	20.39	14.68

5.2 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 5 shows the comparisons between the simulation and the measured results.

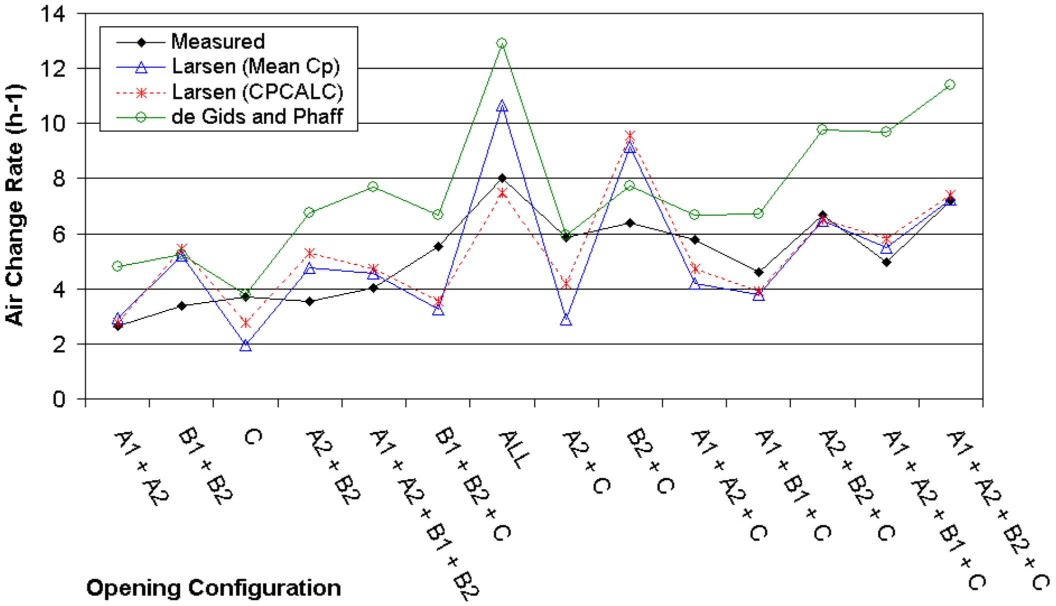

Figure 5. Comparisons between the experimental and simulation results performed into the PowerDomus software for the NOA Building case.

According to the results presented in Fig. 5, its noticed that the Larsen model using the CPCALC method to calculate the pressure coefficient has the best results. When the relative errors for all the obtained results are calculated, the graphical analyzes is verified (Tab. 6).

Table 6. Relative errors for the NOA Building experiment.

Model	Relative Error (%)
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^o 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, $A_2 + C$) where the angle is about 70^o 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.

6. CONCLUSIONS

Several single-sided ventilation simulations through openings were performed in a building hygrothermal and energy simulation software - PowerDomus. The simulations were compared to experimental results carried out in a full-scale wind tunnel at the Japanese Building Research Institute (BRI) (Larsen and Heiselberg, 2008) and from an on-site three-storey, naturally ventilated, office building from the Institute of Meteorology and Physics of the Atmospheric Environment in Athens (IEA, 1996). The idea was to verify the result of single-sided natural ventilation models in controlled and uncontrolled airflow.

Two single-sided ventilation models were tested, the de Gids and Phaff (de Gids and Phaff, 1982) and the Larsen (Larsen and Heiselberg, 2008) models. For the second one two ways to calculate the pressure coefficient were evaluated, the Mean C_P and the CPCALC methods. The first compute a mean C_P value for the wall and the second calculate the pressure coefficient for the center of the opening.

Comparisons between simulations and measured results showed that for both controlled situation presented in the wind tunnel experiment and the uncontrolled on-site experiment, Larsen's model by using the CPCALC calculation presented better results than the de Gids and Phaff and Larsen (with Mean C_P method) models.

Differences on the the air change rate by using the Larsen's model have been noticed. It can be explained by the two methods used to calculate the pressure coefficient. The higher differences for the wind tunnel experiment are justified by the window location, near the corner of the wall, increasing the C_P variation between the two methods.

Using a more detailed model such as the one of Larsen can reduce by a factor of 2 the error made on the air change rate predictions. However, one can observes the high error (minimum of around 20%) resulting from those empirical models. A new accurate model is still needed to evaluate the air change rate by induced single-sided natural ventilation.

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9. Responsibility notice

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