ASSESSING NATURAL COOLING STRATEGIES IN APARTMENT BUILDINGS USING DE-COUPLED INTERNAL-EXTERNAL AIRFLOW SIMULATIONS

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ABSTRACT

Computational fluid dynamics simulations were conducted to investigate the performance of enhanced natural ventilation strategies in an existing multi-storey apartment building in Athens, a typical urban Greek domestic building type. De-coupled airflow modelling was employed to predict the airflow patterns around the case study building at the neighbourhood scale, along with the prediction of the internal airflow patterns and indoor air temperatures at the scale of a single apartment. Implementation of a wind-catcher and a second façade layer have been investigated to enhance the natural ventilation of the building and improve the original single-sided ventilation strategy.

INTRODUCTION

Natural ventilation can provide thermal comfort and good indoor air quality (IAQ) and potentially consume less energy than mechanical ventilation equivalents. Ideally, natural ventilation should be considered at the early stages of design. However, it is possible to introduce natural ventilation systems as a refurbishment study to existing buildings with minimal disruption to the occupants and the buildings' form.

In hot climates the energy required for cooling can be more than twice the energy for heating (Santamouris & Asimakopoulos, 1996), while existing Greek domestic buildings have the highest energy consumption in Europe (Asimakopoulos et al., 2012) representing a substantial opportunity for energy savings. Despite the increasing air-conditioning installations (Yun & Steemers, 2011), with the reported concerns over IAQ conditions due to air-tight buildings and reductions in ventilation rates (Lai et al., 2009), it is worth building owners turning their interest to energy efficient natural ventilation systems.

Furthermore, given the warm, dry climate of Greece (HNMS, n.d.) with the lowest levels of relative humidity and the highest wind speeds in the Mediterranean, it is possible that occupants' thermal comfort expectations can be met through natural ventilation strategies (Santamouris & Asimakopoulos, 1996).

Natural ventilation is one of the most common applications of passive cooling that employs natural forces of pressure difference induced by wind or temperature differences (Santamouris & Asimakopoulos, 1996) and can easily be incorporated into existing buildings. Of these natural cooling strategies, cross-ventilation, night ventilation and wind-catchers can potentially improve the single-sided ventilation, an approach commonly found in highly populated urban areas of buildings with one main exposed façade (Dascalaki et al., 1999).

The aim of the study was to investigate and compare different natural cooling systems expected to efficiently deliver acceptable IAQ; optimisation of individual natural cooling system designs was outside of the scope of this project. An urban multi-storey apartment building was selected in the city of Athens, as a representative example of the urban architectural typologies in Greece for its design, year and type of construction (based on buildings classification by Papadopoulos et al., 2008). With the living spaces located on the front, direct access to natural light and outside air is restricted for the smaller rooms (i.e. kitchen, toilets) as they only have openings into a light well at the rear. This work sought to evaluate the existing single-sided natural ventilation pattern of the selected apartment and propose efficient natural ventilation solutions employing cross-ventilation strategies, use of a wind-catcher, and a lightweight structure of a second façade layer of external horizontal shading systems.

Computational fluid dynamics (CFD) is widely used for the estimation of airflow patterns in and around test spaces. CFD can be employed as a less expensive and time consuming alternative to traditional wind tunnel testing, with greater design flexibility (Niu et al., 2005) that is well-established and increasingly used for the evaluation of health and comfort in spaces (Hajdukiewicz et al., 2013). Being employed by several researchers for the performance evaluation of different wind-catcher designs, it has proven to be an efficient tool in this area of research by having good correlation with experimental results, as described by Montazeri (2011).

Although research has been undertaken previously on the energy behaviour of Greek urban residences and their possible renovation (Theodoridou et al., 2011; Papamanolis, 2006), little research has been carried out on the implementation of passive cooling solutions in existing apartment buildings and their potential performance (Santamouris et al., 2010; Yik and Lun, 2010).

This paper details how changes to the operational pattern and building design (i.e. the utilisation of a wind-catcher and a double-skin façade) assist the natural cooling of the apartment building studied, and improve the original single-sided ventilation strategy, resulting in IAQ enhancement and mechanical cooling demand reduction.

METHODOLOGY

Four different ventilation strategies were evaluated in terms of both indoor air temperature reduction and fresh air distribution. Each system was designed and the apartment studied tested under buoyancy and wind-driven forces subject to different weather scenarios but with the same building design and internal heat gains. Single-sided ventilation, cross-ventilation, implementation of a wind-catcher, and the addition of a lightweight double-skin façade, were the four ventilation strategies analysed in this work.

Figure 1 Floor Plan of case study apartment

In contrast to buoyancy-driven flow, the study of the airflow patterns due to wind-induced ventilation in the spaces examined, required primarily the prediction of the flow around the building. It was therefore decided, due to the computational power required to simultaneously model both internal and external thermal environments, to proceed to individual simulations. Hence, the building and its surroundings were first simulated to obtain the external airflow distribution and pressure values at the location of the openings. These were subsequently included as input values on the buildings' openings for the study of the internal flow.

Furthermore, the building was tested under one weather scenario obtained by a climate analysis of the weather data of the region studied for the cooling period (15^{th} May-15^{th} September, as defined by Greek regulations (Androutsopoulos et al., 2012)). This involved the prediction of the average dry-bulb temperature of the period examined (26^{o}C) and climate studied, and the average value of the local wind speed (3.6m/s at 10m height in open space) under three predominant wind directions (N, E, SW). Thus, the indoor environment was tested under buoyancy and wind-driven natural ventilation sources.

Description of the Building, Surroundings and Ventilation Strategies

The building studied is an existing 5-storey building with a basement and a penthouse, constructed in the early 1970s. It is located in an urban zone of the centre-North area of Athens, and has a typical Mediterranean climate. For the purpose of this work a two bedroom apartment was selected (Figure 1), with living spaces located on the rear, and prime access to daylight and outdoor air from the two openings of the bedrooms. An extended description of the building design and the apartment studied is included in Spentzou et al. (2013), with details of the building's internal gains and its daily operation.

In order to predict the environmental conditions around the building and apartment studied, a survey of the surrounding area of the building was conducted and a three-dimensional map of the size of the surrounding structures, their typologies and uses, as well the altitude of the terrain was generated. At this densely populated area consisting of a mainly continuous line of blocks of multiple apartment buildings with non-constructed spaces at the centre, nine urban blocks (103 properties of 80% residential use) were surveyed, varying from one storey detached houses to ten storey apartment buildings.

As the apartment was originally single-sided ventilated, cross-ventilation was proposed through the existing light well, by maintaining all internal openings open at all times. The light well was then redesigned to implement a four-sided wind-catcher design that has four openings and four separated channels beneath, which is often employed in areas with no prevailing wind, and has been tested and evaluated by several researchers (Montazeri, 2011).

In addition, the indoor spaces were extended by a second layer of fully open openings added at the edge of the balcony, which represent a layer of horizontal external devices of 20cm width that operate in three ranges. The internal heat gains of each space were calculated using dynamic thermal modelling software (IESVE, 2012) by hourly analyses of the indoor environment, preliminary results of which are shown in Spentzou et al. (2013).

For the buoyancy and wind-driven CFD simulations of the four ventilation strategies, a commercial CFD software package PHOENICS (CHAM Ltd., 2013) was used to solve the three-dimensional Reynolds Averaged Navier-Stokes equations using a steady state three dimensional structured Cartesian mesh.

BUOYANCY-DRIVEN SIMULATIONS

When designing the building model, the spaces not investigated were excluded from the simulation in order to reduce computational time and consequently the computational domain was reduced to the external boundaries of the indoor spaces and the adjacent airshaft (Figure 1). The energy equation is solved for temperature, buoyancy is model using the Boussinesq approximation and turbulence was modelled using the k-epsilon model of Launder-Spalding (1974). At each opening, the following condition was imposed on pressure:

$$\Delta p_{loss} = -\frac{1}{2} f \rho U_n{}^2 \quad (1)$$

where, f is the loss coefficient and U_n is the velocity component normal to the opening boundary.

For the study of the buoyancy-driven flow, the velocity components normal to each external opening were 'deduced' [1] with air pressure at the opening equal to the ambient and loss coefficient equal to 2.69. Heat gains due to occupants, lighting, equipment and solar gains were modelled as a volumetric heat source of 164W (bedroom 1), 157W (bedroom 2), 120.6W (living room) and 83.1W (kitchen). All other surfaces were modelled as impermeable no-slip adiabatic surfaces.

The solution was considered converged when the spot values (of pressure, temperature and three components of velocity) at a defined monitoring point in the domain remained unchanged, when the logarithms of the sums of the absolute residual of each variable (errors) in the finite-volume equation were reduced to an acceptable magnitude, and when good source balance of less than 1% for each heat source or sink was accomplished.

The differences on the computational domain properties, number of boundary openings, internal openings, cells and iterations of the four natural ventilation strategies are described as follows.

For the single-sided buoyancy-driven ventilation analysis, the shaft was excluded from the modelling calculations in order to reduce the unnecessary computational time. The two ventilation openings on the bedrooms served as both inlets and outlets of the spaces. The domain size is 6.45×7.70×3.00m and the mesh comprises of 16,184 cells. The computational domain of the cross-ventilation case was then increased by height to incorporate the total height of the air shaft (7.05×7.70×12.80m), and was divided into 79,200 cells.

The performance of the wind-catcher was also analysed for buoyancy-driven flow. The wind-catcher design was added on the top of the existing air shaft as described in the previous case (cross-ventilation) and the z-axis was increased by 4.20m (domain: 7.05×7.70×17m). The four openings on the top part of the wind-catcher have an area of 2.20m^2 on both long and short sides. Partitions on an 'X' arrangement of 5m length were designed with thickness of 7cm. The mesh was refined in this case for the wind-catcher, a finer mesh was created to avoid double cutting of cells[2]. With 259,182 cells in total, they vary in size from 22 to 4 per metre.

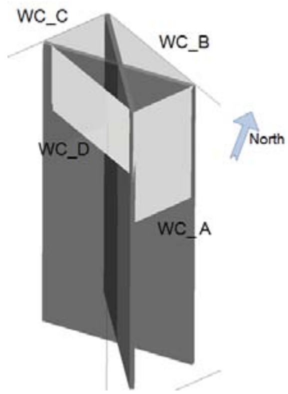

Figure 2 Proposed design of the four-directional wind-catcher.

For the double skin façade (DSF) case, the domain is larger (7.05×9.30×17.00m) on the y axis, due to the addition of a balcony, with 188,784 total number of cells, which incorporated 3 continuous verticaly arranged rows of openings of length 6.35m and heights of 0.80m (DSF1), 1.40m (DSF2) & 0.80m (DSF3) respectively. In addition, a deflective wedge was placed at the bottom of the shaft to channel the airflow directly into the spaces after an evaluation analysis was carried out on the previous cases regarding the performance of the shaft.

WIND-DRIVEN SIMULATIONS

Study of the External Flow

Modelling the building as a stand-alone case was considered an ineffective way to study the flow field around the building considering that the existing building is located in a densely populated urban area, and so analysis of the flow field around the building and its surroundings was required. The computational domain was designed to include the surrounding structures proportional to the buildings outline (as

[1] *"the in-flow value will be deduced at run-time from the mass flow rate divided by the in-cell density and cell area" (Ludwig & Mortimore, 2011).*

[2] Double cutting occurs when the bounding surface of an object cuts a cell more than once. In such cases the solver does not recognise the object, replacing it by the domain material (air).

proposed by the software developer) to enable the efficient investigation of various wind directions.

The surrounding buildings and the building studied were simulated as individual blocks with all openings ‘closed’. The design was simplified to reduce computational time and therefore shading systems, balconies and trees were excluded from the simulation process. The terrain heights were investigated, although after test runs indicated that they only affected the flow field at ground level, it was decided to exclude these from the simulations also. The dimensions of the computational domain are equal to 900m×750m×136.8m. The nine blocks occupy a central area of 40677m^2 (34m was the height of the tallest building) (Figure 6). The probe used to monitor convergence was located at 7.7m from the ground, among the buildings.

A wind object was created occupying the entire domain, of 3.60m/s wind speed at 10m reference height. The wind object creates inflow boundaries at the domain edges with a logarithmic profile on the upwind faces with fixed pressure boundaries on the downward faces, sky and ground plane (with effective roughness height of 0.75m) (Ludwig & Mortimore, 2011). Three dominant directions were examined; North, East and South-West (see climate analysis). The turbulence model employed was the modified k-epsilon model of Chen and Kim that reduces the dissipative nature of the standard k-epsilon model (CHAM Ltd., 2008), whilst the energy equation was not calculated.

The airflow around the building was modelled for three cases; the cross-ventilation study with the building and its simple airshaft (Case ‘0’), the building with the implementation of the wind-catcher (Case ‘WC’), and the building with the addition of the balconies and second skin of openings (Case ‘WC & DSF’) (Figure 7). All modelled at three dominant wind directions of 3.60m/s wind speed. In total, ten simulations of the flow around the building were conducted and the pressure values at the openings were predicted. All simulations reached convergence after 3000 iterations and after approximately ten hours.[3]

In order to be certain that the solution is independent of the mesh resolution; five different meshes were investigated as shown in Table 1 with dense areas located in areas where the flow was complex or changing rapidly. Only the first three meshes converged to an acceptable level. Although meshes 2 and 3 gave similar results, mesh three was chosen because it provided sufficient flexibility to include the complex wind-catcher geometry.

[3] Most of the simulations were performed on a Windows 7 desktop computer with two Intel Xeon E5520 processors of 2.27GHz (2 processors) and 64.0 Gb RAM.

Table 1
Different number of cells for the mesh investigation

Type	Number of cells	
Mesh 1	133×102×39	529,074
Mesh 2	151×119×46	826,574
Mesh 3	162×126×46	938,952
Mesh 4	174×137×46	1,096,548
Mesh 5	211×160×46	1,552,960

Aside from understanding the flow field around the building, the primary objective of the external flow simulations was to provide average pressure values at the position of each opening, for each case that would then be used as input values for the study of the internal flow. Therefore, two-dimensional user-defined objects were created at the size and location of the openings of each case modelled and inform[4] coding was written to predict the average pressure values over each surface. For Case ‘0’, three values of average pressure were predicted for each orientation (two at the location of the bedroom openings and one at the horizontal top opening of the airshaft). For Case ‘WC’, six values (two at the location of the bedroom openings and four at the vertical openings of the top part of the wind-catcher) were predicted, and lastly for Case ‘WC & DSF’ seven values (three at the opening of the total surface of the second façade and 4 at openings of the wind-catcher).

Study of the internal flow

The incident wind on the openings of each of the four cases described previously in the buoyancy-driven analysis, is included in the CFD model as average pressure values on the ventilation openings, as predicted by the external flow simulation of each case. For the internal wind-driven ventilation analysis the location of internal-external openings, the heat gains, and the turbulence and energy models were modelled as described in the analysis of the buoyancy flow, while only small changes to the mesh properties were made when convergence was not otherwise achieved.

For the single-sided wind-driven ventilation case, wind forces in terms of pressure values were added at the two bedroom openings. The orifice equation (Equation 1) was used here and the velocity components normal to each opening were ‘deduced’ as described earlier.

In order to ensure solution stability, the pressure values calculated in the respective external flow cases were modified to zero for the outlets and to positive values for the inlets (maintaining the required pressure difference).

[4] The supplement to the PHOENICS Input Language (PIL) facilitating the input of problem-defining data.

The same principle was employed for outlets when simulating wind induced ventilation in the wind catcher and WC & DSF cases. Furthermore, in the case of wind incident on the wind-catcher, only one of the four wind-catcher openings remained open, in contrast with the buoyancy-driven flow, the one with the highest average pressure value as predicted by the external airflow study.

Consequently, the mesh was refined around the wind-catcher to reduce computational time, and the cross partitions were redesigned as solid wedges, enabling one open channel at a time based on the predominant wind direction. In reality, individual automatically controlled dampers would be located at the lowest part of each channel and the top opening respectively, controlled by the wind pressure on the wind-catcher faces.

DISCUSSION AND RESULT ANALYSIS

Four natural ventilation strategies were evaluated with both buoyancy and wind-driven airflow simulations. In order to examine the airflow patterns around the building, the significance of simulating the building with the surrounding buildings was evaluated. This was done by comparing the simulated pressure values on openings of the building with and without its surroundings (Table 2, Wind-Catcher North and N Detached). It was found that the pressure values on the openings of the detached case could generate a pressure difference of up to six times greater than that of the building with its surroundings (see case with North wind direction), resulting in higher but unrealistic values of air movement inside the spaces (approximately 2 times greater). The unique airflow patterns around the building due to its surroundings and the zones of low and high pressures are shown in Figures 6 and 7.

Table 2
Average pressure values (Pa) on the openings, and pressure difference between the highest and lowest values at the inlets and outlets for each case respectively, from the external flow analysis.

	North	SW	East	N Detached
Natural Ventilation				
Stack top	-2.75	-1.18	-1.32	
Bed 1	-2.47	-1.49	-1.07	
Bed 2	-2.51	-1.45	-1.13	
Difference	*-0.28*	*0.31*	*-0.26*	
Wind-Catcher	North	SW	East	N Detached
Bed 1	-2.46	-1.42	-1.14	-5.82
Bed 2	-2.59	-1.37	-1.14	-5.94
WC A	-2.97	-1.51	4.1	-21.57
WC B	-2.4	-2.39	-0.81	0.8
WC C	-0.24	-0.2	-0.33	1.13
WC D	-2.87	-0.39	-10.8	-18.17
Difference	*-2.35*	*-1.22*	*-5.24*	*-7.07*
Wind-Catcher & DSF	North	SW	East	
Av.DSF	-2.69	-1.91	-2.72	
WC A	-2.92	-1.63	4.52	
WC B	-2.7	-2.56	-0.42	
WC C	-0.29	-0.23	-0.32	
WC D	-2.81	-0.48	-11.2	
Difference	*-2.4*	*-1.69*	*-7.23*	

The external flow simulations provided averaged pressure values at the location of each opening for all cases, as shown in Table 2. The underlined values were applied as boundary conditions on the openings of the apartment in the internal flow investigation. For the wind-catcher case, although pressure values were predicted for all four openings, only the opening with the highest pressure value was used (based on the predominant wind direction) (Figure 2). The pressure difference between the highest and lowest values in each case gives an indication of the expected driving pressures for each internal flow analysis. For the specific site and building design used here, the East wind direction appears to be the most favourable for wind-driven natural ventilation strategies, showing a predicted driving pressure of 5.2Pa (WC) and 7.23Pa (WC & DSF).

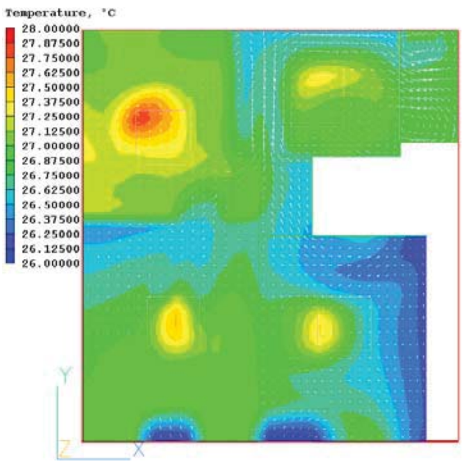

Figure 3 Temperature contours and vectors in plan view (at 1.30m height above the apartment floor level) of the buoyancy-driven flow from the cross-ventilation case (single-sided case)

For the evaluation of the internal airflow patterns, both wind and buoyancy-driven flows were examined. The predicted volume flow rates for all inlet openings are presented in Table 3. For all cases the contribution of wind to the previously buoyancy-driven case is evident; the percentage of the ventilation flow rates increase are given in Table 3 along with the openings acting as inlets for each case. When evaluating the performance in the absence of wind, the negligible airflow movement of the single-sided strategy (~0.03m/s close to the openings) shown in Figure 3, has clearly improved with the implementation of the shaft and further more with the wind-catcher (flow of 0.1m/s at the rear spaces close to the airshafts outlet).

Table 3
Volume flow rates (m^3/s) on the inlets of each case and the percentage of increase compared to each buoyancy ventilation case.

	Buoyancy	**North**	**SW**	**East**	
Single-sided Ventilation	Bed 1	Bed 2	Bed 2	Bed 1	
	0.015	0.588	0.124	0.185	
		3710%	704%	1097%	
Cross-ventilation	**Buoyancy**	**North**	**SW**	**East**	
	Beds	Beds	Shaft	Beds	
	0.368	0.790	0.540	0.757	
		115%	48%	106%	
Wind-catcher	**Buoyancy**	**North**	**SW**	**East**	**N Detached**
	Beds	WC C	WC C+D	WC A	WC C
	0.707	1.036	0.901	1.673	1.765
		46%	27%	137%	150%
Wind catcher & DSF	**Buoyancy**	**North**	**SW**	**East**	
	DSF	WC C	WC C	WC A	
	0.684	0.942	0.774	1.576	
		38%	13%	130%	

The results of the wind-driven simulations from cases 'WC' and 'WC & DSF' both indicate greater volumetric flow rates compared to first two cases. Under an easterly wind direction, the wind-catcher case generated volumetric flow rates nine times greater than those in the single-sided case (Figure 4). Both wind-catcher cases also show the greatest improvement in fresh air distribution. Natural ventilation has improved in 'WC & DSF' case compared to the first two cases as indicated by the volume flow rates on the inlets (Table 3), however, to a lesser extent than 'WC' case. The second layer of openings (WC & DSF) was expected to yield a greater enhancement to the natural ventilation of the spaces than the results suggest.

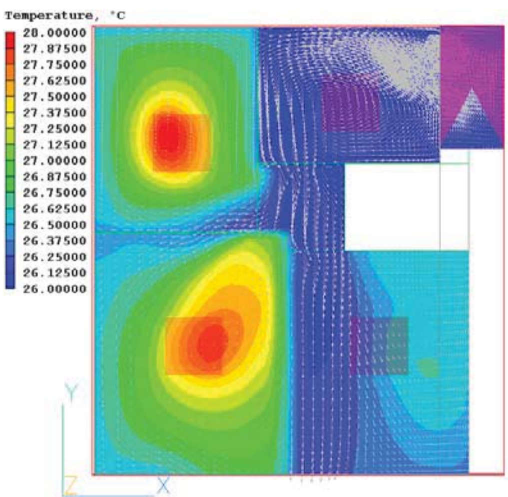

Figure 4 Plan view of the temperature contours and vectors (at 1.30m height above the floor level) of the Wind-Driven flow (East) of the wind-catcher case (case 3).

The addition of the wind-catcher (case 'WC') therefore appears to be the most efficient strategy. The results show maximum ventilation values in the shaft (Figure 5), the kitchen has the greatest improvement in terms of passive cooling ventilation (up to 1°C reduction) and fresh air provision, while the temperature values in the living room were reduced by at least 0.5°C. A better distribution was also observed in the front rooms, assisting the extraction of stale air from the main openings.

Results indicate that indoor air quality in the spaces was enhanced with the implementation of the new natural ventilation strategies, when compared to the previous condition of the single-sided ventilation (Table 3). The exploitation of wind-driven simulations predicted the most favourable wind directions for each strategy, suggesting a possible reduction of the building's cooling demand for the climatic conditions analysed.

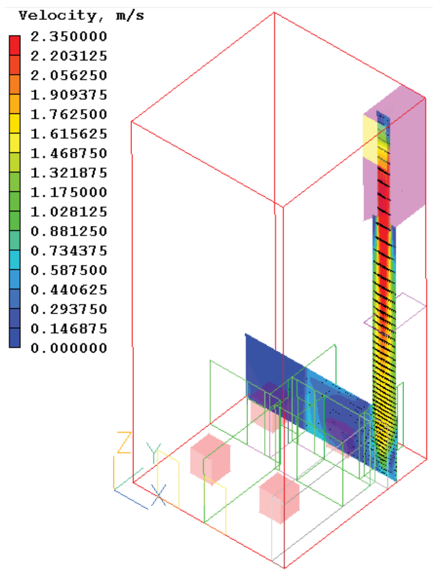

Figure 5 Velocity contours on xz plane, indicating downward air movement from the wind-catcher top opening to the spaces (wind-driven flow from East).

CONCLUSIONS

This paper reports the results of a numerical study focused on the application of different passive cooling strategies under various climatic scenarios in an urban apartment building in Greece. The exploitation of cross-ventilation, the application of a wind-catcher and the addition of a lightweight double skin façade were evaluated.

The ventilation rates of the spaces have shown improvement with implementation of these strategies, relative to the previously single-sided ventilation strategy. Specifically, a reduction in indoor air temperature was predicted in rooms where there was previously no direct access to fresh air, while the volumetric flow rate of fresh air in the spaces increased by up to nine times with the integration of the wind-catcher in the building design. The shaft (cross-ventilation case) provided volumetric flow rate increase up to four times from the originally single-sided ventilation strategy, however the addition of the wind-catcher provided increase in flow rate of up to nine times.

Future work will investigate ways to provide greater passive cooling of the spaces and efficiently reduce the indoor air temperature below the ambient levels. This project will continue with the evaluation of the application of an evaporative cooling strategy on the proposed wind-catcher design that could efficiently provide an adequate temperature reduction that has been evaluated through several published works. Additionally, changes on the percentage of opening of the fenestrations will be further investigated. The effect of various wind directions and higher wind speeds will be analysed as well as maximum values of ambient air temperature of the studied area.

NAMENCLATURE

Δp_{loss}, pressure difference at the openings (Pa);
f, loss coefficient (-);
ρ, density of air (kg/m^3);
U_n, velocity component normal to the opening boundary (m/s).

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