Ventilación natural: estudio aerodinámico mediante CFD de extractores pasivos y captadores de viento

Natural ventilation: CFD aerodynamic study about passive extractor and windcatcher

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Resumen

La ventilación natural se ha ganado protagonismo en los últimos tiempos como una medida de ahorro de energía para edificios. Los dos principios fundamentales de ventilación natural son el tiro natural por diferencia de temperatura, y la fuerza del viento. El artículo pretende analizar la aerodinámica de los captadores y extractores de viento mediante fluido-mecánica computacional, optimizando las geometrías de estos elementos, y dando como producto del trabajo un modelo simplificado para poder tenerlos en cuenta el cálculo aeráulico de las instalaciones de ventilación y climatización de los edificios. Concretamente, se caracteriza una base de geometrías de captación de viento, y se elabora una guía para el diseño de geometrías de extracción ofreciendo varias de ellas como producto del trabajo realizado.

Palabras Clave: Captadores de viento, elementos pasivos, ventilación natural, coeficiente de presiones, CFD

Abstract

In recent years, natural ventilation has won popularity as an energy saving measure for buildings. There are two fundamental principles of natural ventilation: natural draft by temperature differences, and wind force. The purpose of the article is to analyze the aerodynamics of windcatchers and wind-extractors by means of computational fluid mechanics, optimizing the geometries of these elements, and giving a simplified model as a result of the work, so as to include it in the aeraulic calculation of the buildings' air conditioning systems. Therefore, a base for wind catching geometries has been characterized, and a guide for the design of extraction geometries has been developed; several of them are offered as a result of the work undertaken.

Keywords: Windcatcher, passive elements, natural ventilation, pressure coefficient, CFD

1. Introducción

1. Introduction

Currently, there are countless solutions for improving energy efficiency in buildings and their facilities, aimed at reducing their energy cost. To achieve these goals, windcatchers and wind extractors, which are described with more detail below, are rescued from ancient cultures as epidermis elements, of low complexity, that allow developing the natural forces induced by the wind to initiate the air movement inside the building, reducing the consumption of fans and increasing the facilities' efficiency (Allard et al., 2003). However, a double function appears under this slogan, which could further encourage its development and installation: a protection against the rain in the building's air intakes and outlets.

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Figura 1. Captador de viento. Exposición Universal de Sevilla 1992

Figure 1. Windcatcher. Seville World Expo '92

Natural ventilation is applicable only in a limited range of climates, microclimates and types of buildings (Olsen and Chen, 2003). The wind affecting a building's front produces a positive pressure and a negative pressure on the opposite side. This pressure difference, and the pressure differences on the inside of the building, shall promote the air movement. Therefore, to act on the wind, the geometry of the epidermis has to be configured to optimize the positive and negative pressure created by it. Overpressure entails capture, that is air inlet; and suction is the extraction, air outlet. There are many techniques (Santamouris et al., 2006; Naghman, 2008) for the integration in the buildings and the use of natural ventilation. This paper is focused on wind catchers and extractors, assuming that most software for the design of hybrid ventilation systems (most natural mechanic) use simplified models by means of the pressure coefficient which characterizes that element.

Windcatchers

Windcatchers are air capture and discharge systems used to improve the ventilation systems with the aim of reducing the electric consumption of fans, with the consequent energy saving.

Figura 2. Eficiencia del Windcatcher en función de la velocidad del flujo de aire

Figure 2. Windcatcher efficiency in terms of air flow velocity

An optimal configuration benefits from the wind's positive pressure when it is available and reduces the air flow resistance to the minimum in the fan of the tower. This opposite pressure balance can be dealt with changing capture geometry to optimize the catcher's geometry considering the wind's direction and magnitude; this is why they are equipped with an air catching system which basically consists in a mechanism allowing different configurations of the openings and deflectors. The wind capture is defined with an efficiency ϵ calculated as the quotient between the velocity of the air flow expelled from the catcher towards the inside v_i and the velocity of the external wind flow v_{ref} assuming that it acts with a normal component to the opening of the catcher's inlet.

The following Figure shows the results of the experiments carried out by D. Pearlmutter (1996): the defined efficiency and the speed of the driven air flow in terms of the different types of catchers.

At the same time, the chart above offers a good state-of-the-art of wind catchers which was also tested. It can be observed that geometries present a symmetric structure to increase the capture efficiency, provided that the openings are oriented according to the directions where the area's predominant wind usually blows. The first three designs use swinging lowers of different sizes in each opening. Configurations 4 and 5 use fixed deflectors that change the wind direction towards the tower. Models 6 and 7 have an additional central panel combined with the fixed deflectors in the capture unit. The most common windcatchers are models 4 and 5.

The chimney systems have been commercially available in the United Kingdom for more than a century (Santamouris et al., 2006), although until recently these systems were designed for specific solutions in enclosures rather than buildings. The commercial natural ventilation systems offer high air renewal rates, for example, 5 air renewals per hour under relatively low wind velocity conditions (3m/s).

These systems can be combined through an adequate control, using mechanic fans that can be adapted to the facility's wind conditions and face the building's ventilation, or any type of primary air pre-treatment, from heat recuperation of the extraction air to evaporative cooling.

Wind Extractors

Likewise, extractors (Naghman et al., 2008) are used to favor air extraction in chimneys, ducts or ventilated fronts, either reducing the fan's use or improving the air movement in the system.

Extractors can be classified in:

Mobile, such as a wind turbine that moves by effect of the wind, thus producing air extraction.

Fixed, the CFD study is focused on these ones, since the systems are considered a two-function element: a protection function both from rain and animals, and a natural extraction function by effect of the wind, due to its aerodynamic properties.

2. Simplified model

The following facts are set forth to contextualize the need and define the characteristics of the simplified model.

2.1 Explanation

In order to analyze the integration of this technology in the buildings, the "pressure loop method" (Álvarez et al., 2010) will be used. This method has been widely used for duct flow analysis and provides a useful analytical solution to dimension the natural and hybrid ventilation components and systems. The objective is to create a simplified model that allows evaluating how these systems influence the air movement inside the building.

With the aim of further contextualizing the above objectives, we shall consider the case illustrated in Figure 3, where the loops corresponding to each plan can be observed. Each loop represents the air movement from the inlet to the outlet of the building; this movement starts at the outdoor nodes and goes back outdoors, passing through the building's indoor zones.

It is assumed that the illustrated building is to be operated in the natural ventilation mode, and that there is no type of mechanical force promoting the movement. For example, loop 1 includes from the node "a" to the node "s". This loop contains five different segments:

- Inlet segments: "a-b" and "c-d"
- Outlet segments: "i-j" and "s-t"
- Inlet chimney segment: "b-c"
- Outlet chimney segment: "j-s"
- Passing through doors' segment: "e-f" and "g-h"

The nodes pressure are sequentially identified as p_a , p_b , p_c , p_d , ..., p_t , and again p_a . With this notation, the fundamental equation of the pressure loop is:

$$\sum_{loop l} [(p_x - p_y)] = 0 \quad (1)$$

Where the indexes w and y are sequentially permuted in each node as we advance in the previously defined loop. The above equation can also be written as follows:

$$\Delta p_{loss} = \Delta p_{captador} + \Delta p_{extracción} \quad (2)$$

Where:

Δp_{loss} are the pressure losses in loop "i" due to the friction in the inlet, outlet and air movement inside the building.

$\Delta p_{catcher}$ is the pressure increase produced by the wind in loop "i", that is, in the inlet or capture.

$\Delta p_{extraction}$ is the pressure increase in the outlet chimney in loop "i", extraction is caused by the wind.

For a specific loop, the term at the left of the above equation is formed by the pressures opposing to the movement, and in the right term it identifies the pressures promoting the air movement.

Figura 3. Sección vertical del edificio
Figure 3. Vertical section of the building

In the example above, two loops have been identified, so the equation system to be resolved is a system with two interconnected non-linear equations. The two unknown quantities in these equations are the air flows circulating in each floor plan. The interconnection is due to the fact that the air flow in the towers is, in the upper segment, the sum of the flows in each plant. A possible solution method is the Newton-Raphson method, modified to obtain a quadratic convergence. This method is called the "Ralston-Rabinowitz method" using an auxiliary function, and it is used by the PHDC AirFlow Tool (Salmerón et al., 2009; Montazeri, 2011; Montazeri, 2008). Therefore, the models of these systems have to offer pressure increases (inlet) or decreases (outlet) in terms of the wind's velocity and direction.

2.2 Description

In order to quantify the effect of the wind in a building's epidermis area, the following simplified formula is taken from the literature:

$$\Delta P_{viento} = \frac{1}{2} C_p \rho v^2 \quad (3)$$

ρ is the mean air density; v is the wind velocity.

C_p is the pressure coefficient, in terms of the wind's direction/magnitude and geometry of the building. Parameter that defines the simplified model, the pressure coefficient, which depends on the system's geometry and the wind's direction/magnitude. This coefficient is crucial for developing the simplified model, since in a theoretical way, it is a function if the wind's velocity and direction, and of the geometry of the catcher/extractor-epidermis system, and therefore, its value is highly variable.

Thus, the objective is to develop a catalogue of proven values, which allows the analysis of different configurations of wind catchers and extractors under the same conditions. To compensate the opposed effect of the pressure coefficient variability (depending on wind's the direction and incidence angle, they could operate with an effect opposed to the designed one; see next paragraph) there are dynamic capture/extraction systems, previously discussed, which modify their geometry in terms of the variation C_p .

The pressure coefficient can be positive and negative; positive means overpressure in relation to the ambient pressure (catchers), and negative, suction (extractors). Consequently, for the capture the purpose is to create systems with a geometry that allows containing the highest pressure coefficient; and for the extraction, the opposite. A building may involve capture and extraction in its air circulation loop, and the sum of both is the force coming from the wind.

2.3 CFD simulation

The purpose is to simulate a wind tunnel where the capture and extraction geometries will be analyzed, in order to estimate the mean pressure coefficient representing the nominal operation of these systems. Therefore, the CFD FLUENT will be used. The model's basic element is the wind tunnel (Montazeri, 2008), which is modeled as a big cubic model with a dimension of hundred meters to guarantee that it has no effects on the results.

Figura 4. Esquema del "Túnel de viento modelado"

Figure 4. Outline of a "Modeled Wind Tunnel"

Air shall be driven above this tunnel at different velocities and directions, varying the magnitude and direction of the air inlet velocity in each face of the facility. The rest of the contour conditions are referred to the ground, as a wall, and to the surface opposite to the air intake with the condition of flow freedom (air intake or outlet, at pressure null). The analysis for wind catchers (Rupak Biswas and Roger C. Strawn, 1998) and extractors, besides being independent in the simulation, differ in the model:

Catchers:

- They are connected to a building, represented as a rectangular prism, ten meters high, similar to a two-story building, and the dimensions of the ground plan are 6x10m.
- The influence of the catcher's position on the roof is evaluated, simulating the same catcher on the roof's central area and on the side opposed to the wind's incidence frontal side. As an example, the following Figures are given for the model (in green, the possible air inlets, in red, the surface to be studied).

Figura 5. Modelo 4. Posición en central de la cubierta
Figure 5. Model 4. Position in central part of the roof

Figura 6. Modelo 1. Posición en lateral no frontal al viento de la cubierta
Figure 6. Model 1. Lateral position, but not frontal to the wind of the roof.

- The 3D study is simplified to a two-dimensional analysis due to the symmetry both of the problem and the catchers, which simplifies the problem and allows a more detailed study of the catchers, because it reduces the grid's complexity.

Extractors:

- They are analyzed connected to a ventilated front (chamber 15cm wide) since it is an optimal and innovative application covering other applications such as their installation in ducts.

- A three-dimensional study is carried out, since qualitative rather than quantitative results are pursued. Analyzing the main parameters which impact on the air extraction of the ventilated front.
- The purpose is to find a design pattern for the geometry of these elements, capable of reducing the pressure coefficient in the epidermis position where it is installed, and favoring the air suction from the cavity's interior.

Figura 7. Vista simplificada en sección del modelo para el estudio de extractores. Los elementos que componen el modelo son: la vivienda (1), la fachada (2), el extractor (3) y la cámara de aire (4)

Figura 7. Simplified view in the model's section for the study of extractors. The elements composing the model are: housing (1), front (2), extractor (3) and air chamber (4)

The grid (for example, Figure 10) for both models has been optimized according to the particular characteristics of the geometry, with a node distribution in the neighborhood of millimeters near the wind capture and extraction systems, and meters in the rest of the wind tunnel. This variability is consistent with the numerical solution of the problem, and it is identical to that made by the rest of the authors (Rupak Biswas y Roger C. Strawn, 1998). The optimization consisted in creating a grid capable of obtaining pressure coefficient values from the tested wind catchers (Pearlmutter D. et al., 1996), since these values were facilitated by the author himself. The same procedure is used as validation procedure.

Although it is true that the quality control used in the CFD models does not guarantee quality results in phenomena such as boundary layer, turbulence, etc., it has been done this way, because the objective is an average and global value of the effect of these elements on the pressures, together with its applicability: pre-design stage.

The grids of both models present more than a million nodes, grouped in tetrahedral elements, except in the capture systems' regions, where prismatic elements have been used to approximately calculate the effect of the kinetic boundary layer. Therefore, 15 prismatic elements 1mm high have been implemented, both in the capture and extraction system's contour.

A k-epsilon model has been chosen to calculate the turbulence shown in the critical regions after being affected by air flow. The inlet contour condition is a flat laminar profile, which is assumed to reach a high development level throughout its movement, before having an incidence on the building.

3. Results

3.1 Windcatchers

Once the problem has been defined, the catchers can be assessed in the two roof positions. The analyzed capture models are simplified in the following figure:

Figura 8. Captadores de viento analizados en este trabajo. Imagen extraída del programa PHDC AirFlow
Figure 8. Windcatchers analyzed in this paper. Image taken from the PHDC AirFlow software

In the figure, the first five cases represent the five defined models. These five models were chosen because they are typical of the main geometries existing in the global building market.

The following parameters were studied:

Pressure coefficient, as a parameter of the catcher's behavior in relation to the wind, which is an indicator of its aerodynamics and also of its influence on the building's roof. This parameter closes the simplified model described earlier.

Catcher's efficiency, as the quotient between the velocity in the air inlet to the building (red-colored before) and the wind velocity, a relationship between the maximum flow that can enter and that which enters through the velocities.

The zoom made to the problem's interest area (Figure 7) shows a transition zone on the catcher's inside, where part of the air entering the cavity is introduced indoors, and another part goes outdoor through the depression appearing in the wind draft after reaching the catcher. Therefore, the interest surface for calculating the pressure coefficient and the efficiency shall be the entrance to the building itself.

Figura 9. Patrón de flujo de la simulación del captador modelo 1 en la zona central de la cubierta
Figure 9. Flow pattern of the simulation of the catcher model 1 in the central area of the roof

	Cp	Eficiencia Captador/Catcher Efficiency
Mod. 1 Central	1.0	0.26
Mod. 1 Lateral	1.0	
Mod. 2 Central	0.9	0.17
Mod. 2 Lateral	0.5	
Mod. 3 Central	1.0	0.26
Mod. 3 Lateral	0.6	
Mod. 4 Central	0.8	0.15
Mod. 4 Lateral	0.6	
Mod. 5 Central	0.9	0.28
Mod. 5 Lateral	0.7	

Tabla 1. Tabla síntesis de resultados del estudio a los captadores de viento
Table 1. Results summary of the windcatcher study

3.2 Extractors

In relation to the extractors, the purpose is to prepare a design guide of geometries suitable for the use of wind as a natural force for extraction and protection against rain. To analyze the air extraction from the ventilated front, the model is simplified to the analysis of one linear meter, since the aim is evaluating influences and behaviors, so a simplified model provides enough information for taking decisions. This simplified model is introduced into a wind tunnel and air at different velocities is thrust against it (low 1m/s, moderate 2m/s and high 4m/s).

The parameters chosen for the study are:

Height “h”

It is defined as the distance between the roofs (outlet from the air chamber of the ventilated front). This parameter was not included in the study on catchers due to the function difference of each element: the catchers take air from the outside and introduce it in the duct; the height above the surface must be such so that there are no obstacles between the air draft and the catcher. However, the extractor works differently, since the element must create suction from the cavity towards the exterior, therefore the system's control volume must show two effects: the wind crash that creates the depression and at the same time moves the air from the chamber, and the conduction of the wind draft so that it does not enter the chamber.

Figura 10. Malla depurada del volumen de aire para analizar el parámetro altura h
Figure 10. Grid where the air flow has been eliminated to analyze the height “h” parameter

The chosen model corresponds to a roof with anti-rain system where water is collected and canalized towards the roof's drains. Even so, the objective is to assess the influence of the element-opening distance.

The height used in the sensitivity analysis for the selected model is shown in red. The result variable to be analyzed is the flow extracted from the ventilated chamber. The parameter "h" shall vary between 5 and 60cm (5-10-15-20-60).

The following Table shows the relative results for the distance of 20cm (reference):

DISTANCIA/DISTANCE cm	1 m/s	2 m/s	4 m/s
5	155	11	56
10	18	42	80
15	73	48	102
20	100	100	100
60	88	96	121

Tabla 2. Tabla síntesis del análisis de sensibilidad para la altura h (extractor-apertura)

Table 2. Summary of the sensitivity analysis for height "h" (extractor-opening)

The results are shown in % in relation to the reference case, which means that percentages lower than 100 indicates that the extraction flow is reduced in relation to the reference situation.

The Table shows two trends which depend on the wind's velocity: for low velocities (calm situation), it is convenient to put the extractor at a small distance in relation to the opening; however, for high velocities, a greater distance indicates greater suction power.

The cause which may explain the reason why for low velocities it is best to have the element at a small distance is the effect of the secondary draft: for low velocities, the suction due to the aerodynamics of the element and the dragging are similar, so the flow increase is not caused thereby. But at low velocities, the secondary air draft which goes up the external front of the buildings becomes relevant; therefore, it is necessary to conduct it outside the opening area, so that this draft together with the main one creates the suction effect (trail).

Figura 11. Vectores de velocidad para la simulación del modelo representado en la Figura 10: velocidad de viento 2 m/s, y una altura de A: 5cm, B: 10cm, C: 15cm y D: 20cm

Figure 11. Velocity vectors for the simulation of model illustrated in Figure 10: wind velocity 2m/s; height for A: 5cm, B: 10cm, C: 15cm and D: 20cm

When increasing the velocity, it is convenient to separate the element from the opening to avoid its behavior as air catcher (overpressure in the epidermis). The image above shows the plug effect occurring when the wind that reaches the element and the wind draft going up the front try to penetrate through the separation between the element and the opening.

Geometry of the Element

From the bibliographical/theoretical analysis of the optimal aerodynamic geometry, possible harmonizing solutions between manufacturing feasibility and associated cost are outlined. There are two areas to be taken into account in the geometry design: the draft attack area (located in the main direction of the winds of the area); and the area opposed to the attack. In the same way as in an airplane's wing, there is a zone similar to the extrados (attack + air draft conduction), where the air gains more velocity; and intrados (area opposed to the attack), where the draft has less velocity and more pressure.

The purpose of the geometry analysis is to obtain the correct knowledge to avoid:

- Air capture towards the ventilated front.
- Overpressure reduction in the intrados area, since it is the chamber's extraction way.
- Analysis of situations not included in the design: behavior of the element in case that the wind is opposite to the selected attack.

Figura 12. Catálogo de geometrías de extracción diseñadas y modeladas para el estudio
Figure 12. Catalogue of extraction geometries designed and modeled for the study

Case 6 is the case without extraction geometry, and Case 1 is the previous one used as reference. From the geometries, Case 5 is worth mentioning, since it is not symmetrical as the other ones, and it is neither aligned in relation to the axis of the air chamber; it is rather out of place at the edge of the building front to conduct the secondary draft. Simulations are made for a 20cm height “h” and the wind velocities formerly used.

Tabla 3. Tabla síntesis de resultados del estudio del parámetro geometría en extractores
Table 3. Results summary of the geometry parameter study for extractors

CASO/CASE	1 m/s	2 m/s	4 m/s
1	100	100	100
2	90	58	96
3	94	76	93
4	92	72	94
5	106	110	116

The results show that the geometry of Case 5 is the best, with a slight margin over geometry one. The conclusions of the study regarding the analyzed geometries are the following:

- The best results are obtained when drives the secondary draft going up along the front, especially at low velocities when it is similar to the main draft. Therefore, geometries similar to Case 5 are needed, where the lower profile tries to receive and throw that draft out of the entrance opening.

- For high velocities, the draft should not be influenced in the way of geometry one. Or, if there is an influence, it should not be conducted towards the opening (overpressure).
- Geometry 3 in relation to 4 adds a material and cost reduction which is interesting, but the lower part should be closed to avoid this quiet area.
- The extractor has to be placed in relation to the wind's main direction in the area, but due to its variability, the fact that other orientations are not adverse has to be considered. In this manner, geometries like number five, which are optimal for the main direction, can be negative for the other wind directions, and geometry one can be more convenient because it is more isotropic in the other orientations. This fact motivates the use of wind turbines, which are easy to install and have a greater efficiency than static ones.
- For high velocities, even without geometry, the extraction is good, so, besides keeping it away from the opening, the geometry with the lowest aerodynamics coefficient (area which faces the wind flow) is preferable.

4. Conclusions

- The studies considering the wind as a natural ventilation promoter have to take into account its variability, regarding magnitude and direction, and the influence of external constraints of the environment surrounding the element, in order to avoid obstacles.
- Any passive technique requiring the impulse of air from the outside must include the installation of a wind catcher that increases the efficiency and can be combined with mechanical systems which improve the system's manageability.
- The static wind extractors are recommended when used as anti-rain roofs. So, the aerodynamics of these elements has to be taken into account if we seek to foster the natural use of the wind's force. Their competitors are the wind turbines, since they are considerably efficient in terms of its simplicity and reliability.

- Currently, the discussed work has been implemented in the PHDC AirFlow Tool (Salmerón et al., 2009) for the pre-design of passive and hybrid evaporative cooling systems for buildings.

5. Referencias / References

- Allard F., Santamouris M., London, James and James (2003), "Natural Ventilation in Buildings, a design handbook". Capítulo 2.
- Álvarez S., Molina J.L., Salmerón J.M., Sánchez F.J., Sánchez J. (2010), "The architecture and engineering of downdraught cooling". Capítulo "PERFORMANCE ASSESSMENT METHODS", pág.148-168. Londres.
- Montazeri H. (2011), "Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers", *Building and Environment*, volumen 46, 370-378.
- Montazeri H. and Azizian R. (2008), "Experimental study on natural ventilation performance of one-sided wind catcher". *Building and Environment*, volumen 43, 2193-2202.
- Naghman Khan, Yuehong Su, Saffa B. Riffat (2008), "A review on wind driven ventilation techniques", *Energy and Buildings*, volumen 40, 1586-1604.
- Olsen E., Chen Q., (2003), "Energy consumption and comfort analysis for different low energy cooling systems in a mild climate". *Energy & Buildings*, volumen 35, 561-571.
- Pearlmutter D., Erell E., Etzion Y., Meir I.A. and Di H. (1996), "Refining the use of evaporation in an experimental down-draft cool tower". *Energy and Buildings*, volumen 23, 191-197
- Rupak Biswas y Roger C. Strawn (1998), "Tetrahedral and hexahedral meshadaptation for CFD problems". *Applied Numerical Mathematics*, volumen 26, 135-151.
- Santamouris M., Wouters P., Earthscan (2006), "Building Ventilation, the state of the art". Capítulo 2.
- Salmerón J.M., Sánchez J., Ford B., Van Steenberghe T., and Álvarez S. (2009), "Passive and hybrid downdraught cooling in buildings and software for design". *REHVA JOURNAL*, pág. 34-39.