Alternative solution proposal to improve the air change in light shafts based on flaps

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ABSTRACT

Outdoor air change qualifies the air that enters into the buildings. The outdoor air moves freely along the urban mesh favoured by the wind forces and stresses. Buildings, trees and other constructions alter the natural air flow pattern inside the cities, creating stagnated air masses in those wind-protected regions. Some outdoor spaces such as light shafts and confined light shafts inhibit the correct exchange of the stagnated air with fresh air coming from the outskirts and suburban areas.

The research proposed based on computational simulations tries to evaluate the susceptibility of several light shafts to infer the air change of their air by placing flaps close to their upper opening, where fresh air gets into exhausting the stagnated one. The flap is located over the opening aims to change the air flow pattern inside the light shaft by using Venturi effect partially sucking the stagnated air.

Results show that in the proposed cases the air velocity distribution is changed along the light shaft, affecting the air flow related to the reference case. The air flow through the opening increases ten times when the flap is placed. Nevertheless, the impact of the flap in the air change is negligible because the mean age of the air inside the light shaft does not decrease. It would be necessary to propose new flap models, which will affect the distribution of the air inside light shafts to improve the air change.

KEYWORDS

Outdoor air quality; light shaft; natural ventilation; CFD; air change efficiency.

1 INTRODUCTION

The concept of “light shaft” has been developed in South European cities due to the regulations on building depth. It is defined as the confined outdoor space formed in and between the buildings whose principal function is lighting and ventilating indoor spaces in a natural way (AI-Azzawi, 1994).

Light shafts are designed to provide light to those indoor spaces that cannot take the light directly from outdoor spaces due to its location into the building. They are also very important in terms of ventilation but usually are not designed for that purpose, hiding the air access (Ng, 2008) (Chen, 2009). The quality of that air is also lower than the indoor air. Outdoor air flows freely through the city even though emissions of combustion gases and other pollutant sources contaminate it (Buccolieri et al, 2010) (Chavez et al, 2011) (Holford and Hunt, 2000) (Germano et al, 2005).

The dispersion from light shafts and other enclosed spaces was evaluated by Hall et al. (1999). Ok et al (2008) developed an experimental study of surfaces openings on air flow caused by wind in light shafts. The impact of several outdoor space geometries on the air quality was analysed by Padilla-Marcos et al. (2016) using the age of the air and efficiency concepts defined by Sandberg (1981). None of them attended to how the air quality depended on the shape and dimensions in a vertical, narrow and generally closed outdoor space, that is, a confined outdoor space. The lack of a deep study of the quality of the air in light shafts in urban environments related to the design of the confined outdoor spaces (Feijó and Meiss, 2011) favoured a generic analysis methodology showing the aspects required regarding the architectural design of these spaces. It has been demonstrated that the air quality and its renovation is affected by the architectonical configuration of the models and the aero-dynamical phenomena of the environment. This methodology assesses the impact of the architectural configuration of the building with a light shaft and its ability to change the air.

DEVELOPMENT OF TWO-DIMENSIONAL MODELS

1 METHODOLOGY

After the assessment of the three-dimensional (3D) analysis of the air behaviour and the age of the air in several light shafts considering its two-dimensions (2D) and proportion, the quality of air renovation inside them can be addressed in an objective way.

The cases of study have been simplified with the aim of reducing the data files processing load and a minimization of the computing cost in future studies. Cases are developed 2D instead of 3D. The “y” axe, which determines the transversal dimension to the normal (the predominant direction of the wind in the light shaft) was eliminated. The reason was that this dimension provided less essential information to the simulation.

After the simplification, it is hypothesized that, when moving from a 3D model into a 2D one, the capacity of the air to flow freely in the horizontal plane is annulled. To verify this, a study of the 2D case was developed in the plane of symmetry. The choice of this plane entails that the 2D analysis corresponds to the representation of a 3D model developed infinitely along the normal direction to the simulation plane.

The representation of the movement of the air in the inner light shafts verifies that it is affected mainly in the vertical plane of the axis of displacement by the action of the wind, which produces a turbulent displacement. In the transverse direction, the movement of the air is mainly conditioned by the walls of the light shaft.

The impact of these factors into the capacity of the renovation of the air located in the inside of the light shafts was studied, according to the usual formal configuration in the Spanish architecture tradition. From all the studied cases, a comparison between Case 1 and Case 2 (Figure 1) was made. Case 1 was an isolated light shaft surrounded by a ring-shaped building and Case 2 were two parallel transversal blocks. Both cases were chosen due to their similarities regarding the cut in the symmetry plane of a 3D model and the infinitely developed case. It was observed that the efficiency of those cases implies just a ± 1.4% difference, and case 2 obtained better results.

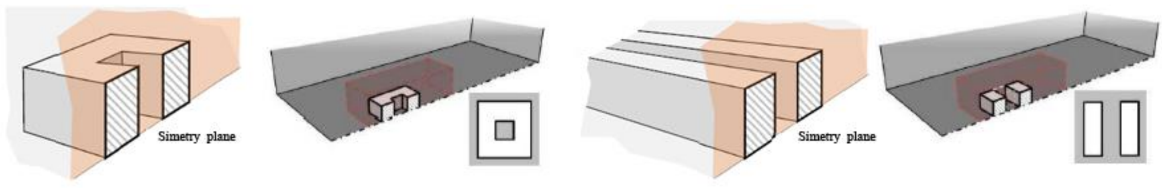
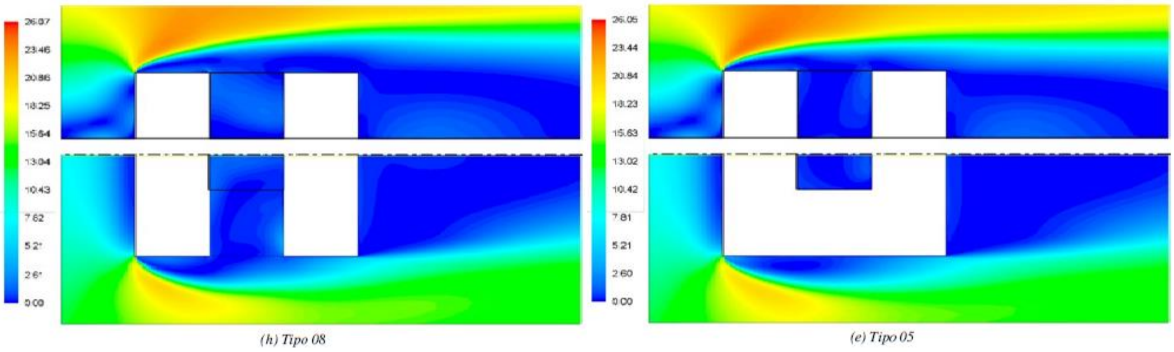


Figure 1: Building model discretization

Resembling the outside space as a continuous outside space or a corridor, the moving air undergoes acceleration when it approximates the solid built due to the reduction of its effective section. The air has no other lateral escape routes to distribute the pressures. The distribution of the age of the air and, therefore, the outside space efficiency, change in comparison with the 3D studied cases. However, the behaviour pattern of the air inside the light shaft once the consideration has been assumed, should take approximated guidelines to those obtained from the 3D analysis of Case 2 (Figure 2).



(h) Tipo 08

(e) Tipo 05

Figure 2: Dynamic outdoor air pattern

After the demonstration of the viability of this simplification, it is necessary to achieve a reinterpretation of the boundary conditions that were taken for the calculation of the cases. These boundary conditions require the specification of the variables that take place in the fluid dynamics: the vectorial influence of the velocity, the pressure, the tension and the transversal friction, as well as the dimensional reduction of the turbulent components of intensity as the turbulent energy and its disposition.

An adjustment of the variables should be done due to the elimination of one of the dimensions of the model. Thus, the physical variables such as the volume and volume required to calculate the minimum renewal time in the 3D model become dependent variables of the third dimension omitted. In order to achieve the transposition of the 2D models to the 3D models, the product of the 2D geometric variables (height of the domain and vertical section of the light shaft) will be conducted. Therefore, it is possible to achieve the evaluation of the minimum renovation time in the domains with its air flow admission variables and the light shaft volume.

$$Q_{3D} = \bar{u} \cdot h \cdot w \ldots \rightarrow Q_{2D} = u \cdot h \cdot (1m) \tag{1}$$

$$V_{pt_{3D}} = H \cdot L \cdot W \ldots \rightarrow V_{pt_{2D}} = H \cdot L \cdot (1m) \tag{2}$$

Where: Vpt_{3D} is the air contained in the light shaft; H the light shaft height; L the light shaft length (in the longitudinal axe, “x”); W the light shaft width (in the transversal axe, “y”); Vpt_{2D} the unitary air volume contained in the light shaft; Q_{3D} the admission air flow to the domain; 4+ the average velocity of the wind profiler; h the height of the domain; w the width of the domain; and Q_{2D} the unitary air flow in the admission of the domain.

Thus, it can be obtained that the air flow in the computational domain admission, or control domain, is the result of multiplying the average velocity of the wind profiler in the domain per its height. The volume of the air in the light shaft is the result of the product of it two-dimensions obtained from the built surfaces, which have been sectioned by the plane of the 2D analysis (Figure 3).

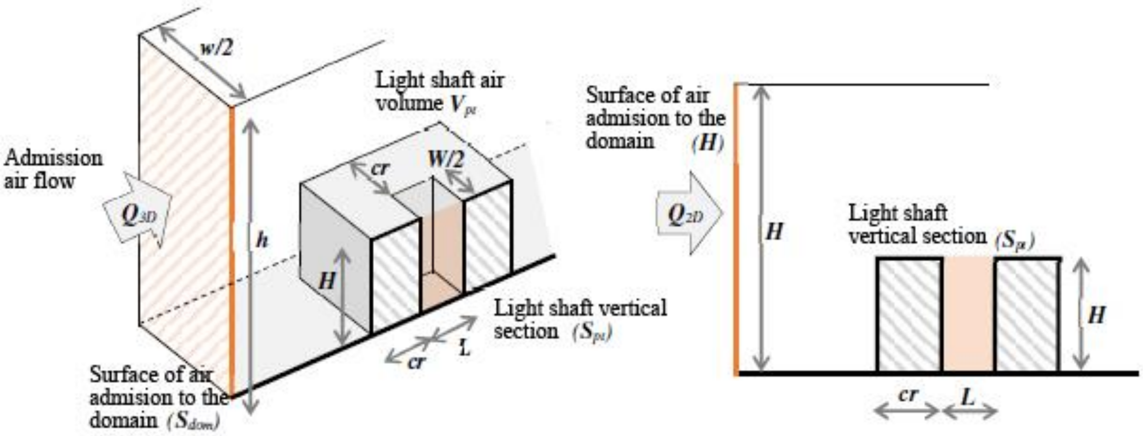


Figure 3: Computational domain discretization

This explanation demonstrates that the simplification to the 2D simulation models is adequate since these they are accurate enough to analyse the efficiency of the air renovation of the light shafts. The correspondence of the efficiency values of both cases is demonstrated in the 3D light shaft model, used as a reference case: 6x4x42 meters long, wide and high respectively (Table 1 and 2).

Table 1: Results obtained from the 2D simulation of the base case, dimensions 6 m x 42 m.

	Unitary volume	**Unitary air flow**	**Average age of the volume**	**Control efficiency**
patio 6x42	252 m³	0.04857 m³/s	152658.810 s	1.636 %

Table 2: Results obtained from the 2D simulation of the base case, dimensions 6 m x 42 m.

6x42 (2D)	**6x2x42**	**6x3x42**	**6x4x42**	**6x5x42**	**6x6x42**
1.70 %	1.06 %	1.40 %	1.72 %	2.00 %	2.24 %

2 RESULTS. IMPROVEMENT OF THE RENOVATION EFFICIENCY AND AGE OF THE AIR OF THE LIGHT SHAFT

After the analysis of the impact of the light shaft in the renovation of its air, considering its design parameters and after the model simplification, the behaviour of this spaces in the case of the disposition of some internal elements, which work hindering and perturbating the air that passes through, was studied.

The modification of the air behaviour around the light shaft can be achieved by the modification of the parameters that determine its movement. Making the convenient modifications it could be possible to change the behaviour of the fluid in order to improve the health and comfort conditions of the ventilation inside the light shaft reaching an upgrade in its air renovation.

To study that, four 2D cases have been proposed. These cases represent the central cut of the same light shaft described below, where the wind velocity is 6m/s in a height of 100 m over the building. Two of the cases had a triangle-shaped flap with the base on the top and the opposite vertex in the middle of the top border of the light shaft. The dimensions of it are 2 m base, 3 m high, which implies an area of 6 m².

2.1 Case A

It is a light shaft of 6 m wide and 18 m high shaped by a flat roof building of 12 m wide. Case A.1. It is the study of the described light shaft without a flap (Table 3).

Table 3: Renovation efficiency in a light shaft of 6 m x 18 m shaped by a flat roof building of 12m wide

CASE A.1	Unitary volume	Unitary air flow	Average age of the volume	Control efficiency	Relative efficiency
Control domain	1908 m^3	60369 m^3/s	563.1 s	2.81 %	-
Light shaft	108 m^3	0.176 m^3/s	783.4 s	2.02 %	39.16 %
Upper third	36 m^3	0.176 m^3/s	759.3 s	2.08 %	13.47 %
Central third	36 m^3	0.176 m^3/s	767.1 s	2.06 %	13.33 %
Lower third	36 m^3	0.176 m^3/s	823.8 s	1.92 %	12.41 %

Case A.2. It is the study of the described but with the disposition of the flap (Table 4).

Table 4: Renovation efficiency in a light shaft of 6 m x 18 m shaped by a flat roof building of 12 m width with a flap

CASE A.2	Unitary volume	Unitary air flow	Average age of the volume	Control efficiency	Relative efficiency
Control domain	1908 m^3	61490 m^3/s	572.5 s	2.71 %	-
Light shaft	108 m^3	1827 m^3/s	834.4 s	1.86 %	3.54 %
Upper third	36 m^3	1827 m^3/s	678.5 s	2.28 %	1.45 %
Central third	36 m^3	1827 m^3/s	763.9 s	2.03 %	4.29 %
Lower third	36 m^3	1827 m^3/s	1060.8 s	1.46 %	0.93 %

2.2 Case B

It is a light shaft of 6 m wide and 18 m high shaped by a gable roof with a slope of 45º in both of its sides, which stand above the top of the building that has a width of 12 m.

Case B.1. It is the study of the described light shaft without a flap (Table 5).

Table 5: Renovation efficiency in a light shaft of 6 m x 18 m shaped by a sloped roof building of 12 m wide

CASE B.1	Unitary volume	Unitary air flow	Average age of the volume	Control efficiency	Relative efficiency
Control domain	**1833 m^3**	**55928 m^3/s**	**1378.1 s**	**1.19 %**	**-**
Light shaft	**108 m^3**	**0.09 m^3/s**	**3230.6 s**	**0.51 %**	**18.57 %**
Upper third	**36 m^3**	**0.08 m^3/s**	**2133.3 s**	**0.67 %**	**8.22 %**
Central third	**36 m^3**	**0.09 m^3/s**	**3331.6 s**	**0.49 %**	**6 %**
Lower third	**36 m^3**	**0.09 m^3/s**	**3928 s**	**0.42 %**	**5.09 %**

Case B.2. It is the study of the described but with the disposition of the flap (Table 6).

Table 6: Renovation efficiency in a light shaft of 6 m x 18 m shaped by a sloped roof building of 12m wide with a flap.

CASE B.2	**Unitary volume**	**Unitary air flow**	**Unitary air flow**	**Control efficiency**	**Relative efficiency**
Control domain	**1833 m³**	**55935 m³/s**	**1685.1 s**	**0.97 %**	**-**
Light shaft	**108 m³**	**0.413 m³/s**	**3175.7 s**	**0.52 %**	**4.12 %**
Upper third	**36 m³**	**0.413 m³/s**	**2391.5 s**	**0.69 %**	**1.82 %**
Central third	**36 m³**	**0.413 m³/s**	**3397.9 s**	**0.48 %**	**1.28 %**
Lower third	**36 m³**	**0.413 m³/s**	**3131.7 s**	**0.44 %**	**1.17 %**

The analysis of these cases will provide the knowledge of how the base case and its different modifications work. In order to achieve it, the data obtained in the control domain has been compared. It implies the study of a total dimension of 27 m upstream from the centre of the light shaft and 51 m downstream from the same point. The vertical dimension was 30. All these measures are modular dimensions of the width of the building (12 m).

The resulting value of the unit flow was analyzed in relation to the height of the vertical projection of the admission surface to the control domain. It is verified that the value obtained from the simulation is closed to the calculated value due to the influence of the wind. The differences in the air flow value between these models are due to the variation in the pressure distribution because of the effect of the build volume. The average age of the air volume allows the determination of its quality. That is, the lower the age of the air, the less its exposition to the pollution by the urban surrounding. The light shaft relative efficiency is evaluated in relation to the control domain previously defined. This allows the evaluation of the impact of the obstruction of the wind to the air flow, which changes the air behaviour inside and outside the light shaft. The relative efficiency analyzes the behaviour in the interior of the light shaft by the exclusive influence of the movement of the outside air near the top of the light shaft. It is here where the obstacle is located in order to modify the kinetic effect of the turbulence and the trajectory of the moving air.

It is necessary the graphic definition of the dynamic and turbulent air models, which determine the results for the analysis of the impact in its behaviour to design architectonical guidelines to improve the process of the air renovation.

The conclusions related to the quality of the air renovation and the light shaft are achieved after having the numerical results. It is observed that the best efficiency is achieved in Case A.1. The global efficiency is close to 3%, due to the low renovation capacity. Case B.2 suffers a decrease of 30% in its domain efficiency in comparison with Case A.1 due to the blockage of the air inside the light shaft. This dam is because the new location of the re-adhesion phenomenon happens further from the top of the light shaft than in Case A.1. The ridge of the sloped roof locates the “takeoff point” higher than in Case A.1, causing a separation, so the air movement dynamic cannot affect inside the light shaft.

Comparing the efficiencies obtained in the results tables (Tables 3, 4, 5 and 6) it is possible to observe that the admission air flow in the light shaft is lower in Case A.1 than in the rest of the studied models. The obstacle element located in the top of the light shaft in Case A.2 tries to change the movement of the air to introduce it into the light shaft and improve its distribution. This can be achieved only by multiplying per 10 the air flow. However, the improvement in the efficiency of the light shaft is not achieved. In fact, the average efficiency descends 50% in comparison with the base case. It is observed that the increase of the velocity does not necessarily imply an improvement in the efficiency.

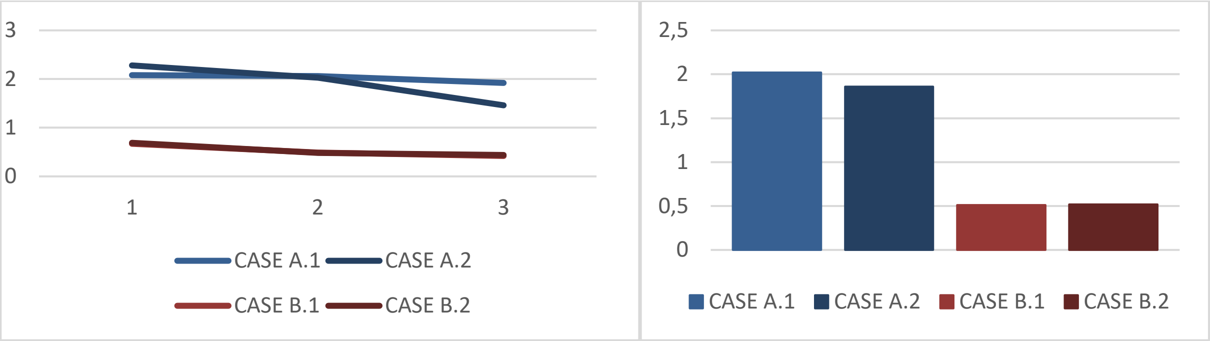


Figure 4: Control efficiency in every light shaft third and control efficiency in the total light shaft.

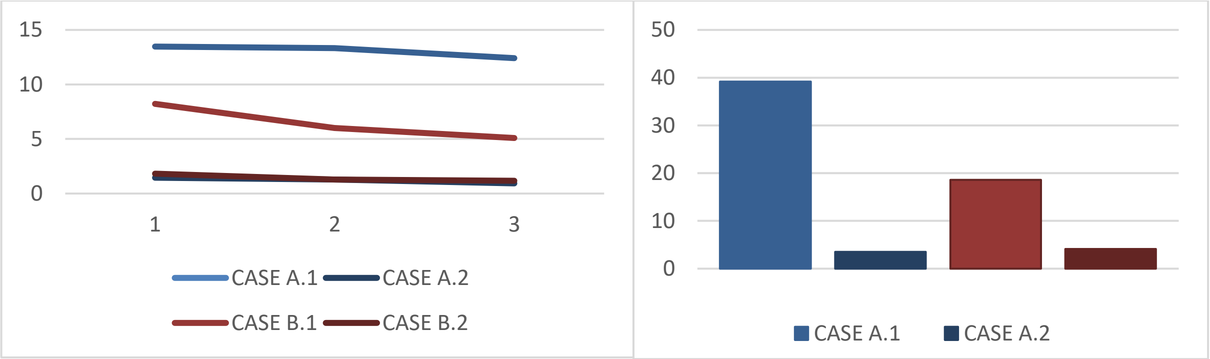


Figure 5: Relative efficiency in every light shaft third and relative efficiency in the total light shaft.

In the graphics (Figure 4 and 5), it is possible to observe that the control efficiency is higher in the flat roof cases. It only implies an improvement in the upper third because at the same time it caused an effect or standstill in the lower third. In the central third, the values are very similar in all cases. In model B, it is possible to observe that the control efficiency values do not change significantly in any of the light shaft thirds or even considering the totality of the light shaft.

By studying the relative efficiency of the light shaft, it is possible to observe that the behaviour of each case is different from the others. The best results are obtained in Case A.1, which are higher than the results obtained in its equivalent case but with the flap. The values obtained in the model B.1 are also higher than the values obtained in B.2. In the two flap cases, very similar results are obtained, not only in each third of the light shaft but also in the totality of the light shaft.

The analysis of the distribution of the age of the air in the domain (Figure 6) shows a standstill that happens in Case A.2 in the lower third of the light shaft and in the totality of it.

In Figure 8, it is possible to observe a change of direction in the movement of the air in the top of the light shaft. This increases the reflow phenomenon observed in Case B.2. In that model, the air downstream, older than the “clean” air, change the direction and enters the light shaft as admission flow, so even though the renovation flow has been increased, this air has already passed the exchange process. This phenomenon causes a cyclic return of the air, which implies a decrease in efficiency. In conclusion, it is possible to observe that what was thought as a strategy of efficiency improvement of the air renovation has ended as a downturn of its work due to a design based on an unreal aerodynamic logic.

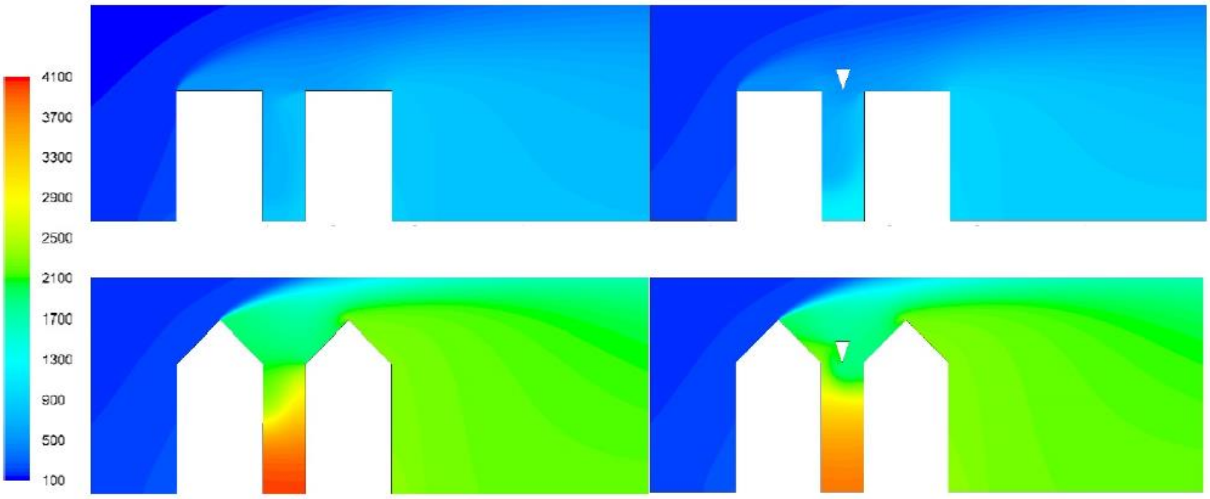


Figure 6: Distribution of the age of the air in the light shaft. Case A.1, Case A.2, Case B.1 and Case B.2

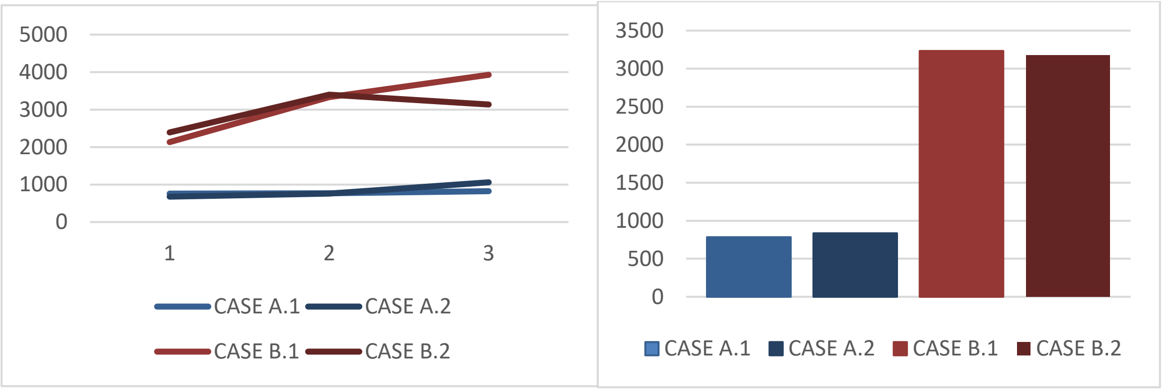


Figure 7: Age of the air average in every light shaft third and age of the air average in the total light shaft

In the graphics (Figure 7), it is possible to observe that the age of the air is lower when there is an obstacle in the middle of the top of the light shaft than when the building has a flat roof, and higher in the case of the sloped roof. In spite of the upgrade, it is not very significant in any case. Studying the different thirds of the light shaft, it can be observed that the central third presents similar values in the different cases without significant variation when there is a flap. In the upper third, the greatest ageing happens in Case A.1, but at the same time, the age of the air in the lower third of this case is 500 seconds older than in Case A.2. Studying the cases of the sloped roof, it is possible to observe that the disposition of the obstacle causes an increase of the age of the air in the upper third. Nevertheless, a significant improvement in the lower third, almost 1000 seconds less in the average age of the air, has been observed.

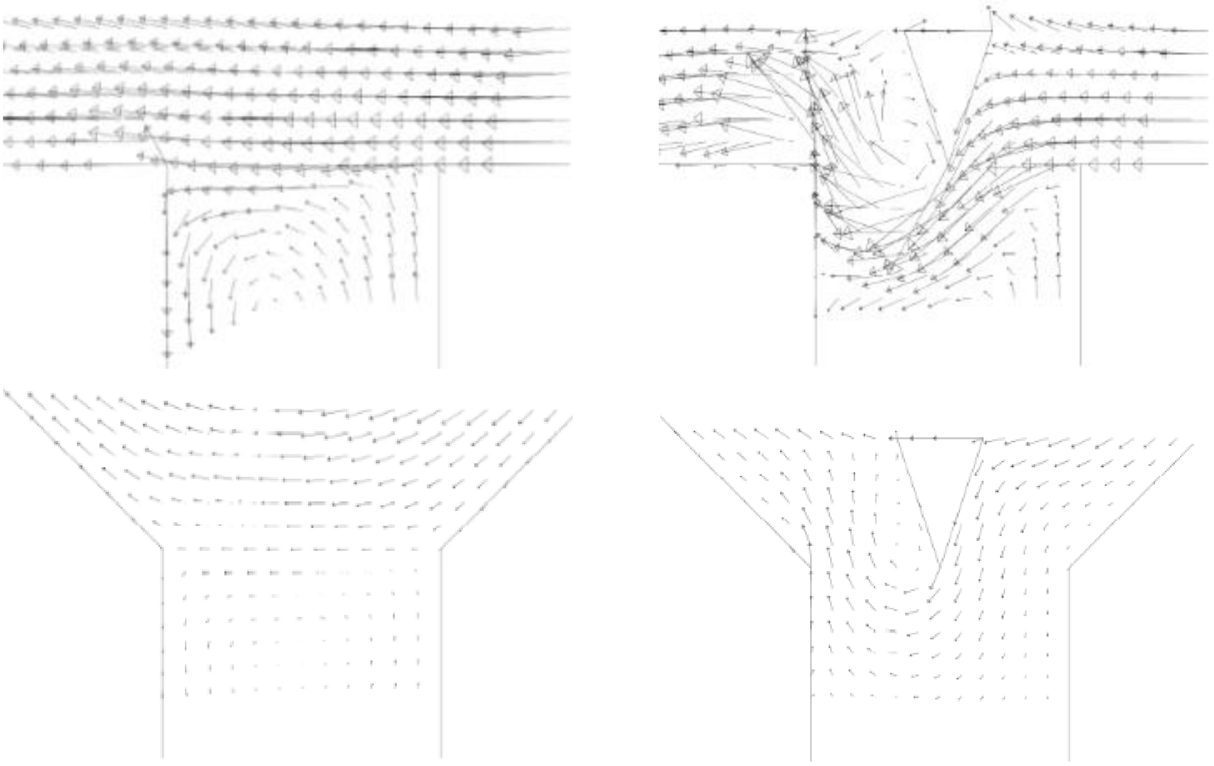


Figure 8: Vectors of movement of the air in the top of the light shaft. Case A.1, Case A.2, Case B.1 and Case B.2

3 CONCLUSIONS

The efficiency of light shaft air renovation determines the quality in which the air provided to the buildings has health conditions. The concept of the age of the air is used to evaluate the average time that a group of air particles stay inside a computational model.

It has been demonstrated that the 2D simplification of the models proposed for the CFD simulations makes the analysis easier, which implies reducing the computational times and cost. This model obtains a precision of ±1.4% in comparison with the equivalent 3D models previously studied.

The study of the renovation efficiency in the four Cases (A.1, A.2, B.1, B.2) shows that it is higher when the light shaft is directly open to the exterior than when there is an obstacle located in the middle of it, trying to change the movement patron of the air masses. As a result, it is possible to observe that Cases A.1 and B.1 have values between 39.21% and 18.6% of efficiency. Meanwhile, Cases A.2 and B.2 only get an efficiency between 4.1% and 3.5%.

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