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A new application model of building ventilation with light shafts: a proposal based on case study assessment*

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Abstract: There is a lack of studies concerning both the quality of air entering buildings from light shafts and its impact on energy consumption. A combined isothermal analysis of several factors such as urban environment and wind, along with the dimensional conditions of the building, facilitated the assessment of the light shaft to promote air change. The aim of this study was on the impact of architectural design on the quality of the incoming air from light shafts. The capacity of light shafts to provide air change with urban air was evaluated using the concept of air change efficiency. This is determined by the environment, the dimensions, and the proportions of the building containing a light shaft. These were simulated using computation fluid dynamics (CFD) techniques which were experimentally validated. This concept requires the definition of an ideal control domain for comparative evaluation in different cases. For the case studies evaluated, it was verified through numerical analysis that the longer the light shaft in the wind direction was, the better the air change efficiency. It was confirmed that light shafts up to 12 m high and with height/length (H/L) rates lower than 3 were those achieving the best efficiency. The study provided several evaluation tools of a design of this type of outdoor space according to the criteria of air change content. An equation is presented defining the value of the air change efficiency for the outline of architectural design strategies intended for buildings with air shafts.

Key words: Outdoor air quality; Light shaft; Natural ventilation; Computation fluid dynamics (CFD); Air change efficiency
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1 Introduction

The current urban configuration of South European cities, conditioned by the regulations on building depth, has encouraged the existence of a kind of confined outdoor space, traditionally called "light shaft". Outdoor spaces are those building voids on the urban mesh that are used for communicating the buildings and for lighting and ventilating indoor spaces in a natural way (Al-Azzawi, 1994).

Light shafts respond to the need to provide light to those indoor spaces in buildings that cannot directly access open outdoor spaces such as streets or courtyards. Apart from lighting, light shafts are commonly used by users to ventilate indoor spaces, something which is not appropriate since light shaft design is mainly focused on solving the problem of natural lighting of buildings. Regulated and existing light shaft dimensions hinder the access of air into the interior of the dwellings (Coronel and Álvarez, 2001).

Indoor ventilation using these confined outdoor spaces is a functional consequence which, in most cases, is not considered in its design (Ng, 2008; Chen, 2009). However, the quality of the air which is supplied through these spaces is clearly diminished in comparison with free atmospheric air because of the

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configuration in urban areas (Holford and Hunt, 2000; Germano et al., 2005). In addition, non-controlled ventilation or an incorrect high flow promotes a waste of energy during the heating and ventilating process (Guillén-Lambea et al., 2016).

The movement of air in cities is mainly caused by wind, which creates a flow between suburban environments surrounding them (Buccolieri et al., 2010). In the urban environment, "fresh" air coming from the suburban regions is polluted due to the emissions of combustion gases (Chavez et al., 2011) or other pollutant sources. Thus, the air is involved in a continuous pollution process. The forced air stream fosters natural air change in cities and their outdoor spaces (Hang et al., 2013). Confined outdoor spaces, such as light shafts, reduce the ability of the air to be exchanged. This inability is due to both the obstruction of the flow and wind deceleration (Ryu and Baik, 2009) caused by the friction of urban surfaces. Together these determine the air quality (Grimmond and Oke, 1999; Hall et al., 1999).

The air quality in urban environments is largely dependent on the emission rate of pollutants, the placement of their sources, and the partially random and chaotic track of the displaced air masses in the city caused by the wind (Amorim et al., 2013).

Hall et al. (1999) evaluated the dispersion from courtyards and other enclosed spaces. Then, Ok et al. (2008) developed an experimental study of the effects of surface openings on air flow caused by wind in courtyards. Padilla-Marcos et al. (2016a) analyzed the impact of several outdoor space geometries on air quality using the age of the air and efficiency concepts defined by Sandberg (1981). None of them attended to how air quality depended on the shape and dimensions in a vertical, narrow, and generally closed outdoor space, which we call a confined outdoor space. The lack of a deep study of the quality of the air in light shafts coming from urban environments related to the design of the confined outdoor spaces (Muñoz and Meiss, 2011) promoted a generic analysis methodology showing the aspects required with regard to the architectural design of these spaces.

The methodology sets a sequence of steps in order to evaluate several architectonical cases simplifying the parameters which have been observed to provoke a better impact on the air change in light shafts. In previous work, it has been proven that the architectonical configuration of the models and the aerodynamical phenomena of the environment affect both the air quality and its renewal process. This methodology assesses the impact of the architectural configuration of the building with a light shaft and its ability to change the air. The aerodynamic behaviour in the vicinity of and inside the light shaft, which affects energy conservation inside spaces, is the only parameter considered.

If light shafts are made more efficient for air change, indoor ventilation demands less energy to achieve a comfortable indoor climate.

The aim of the study is to identify those aerodynamic patterns of buildings with light shafts, where architectural design parameters are involved in the behaviour of the surrounding air (Holford and Hunt, 2003). The purpose of the analysis is to provide technicians, planners, and designers with the tools for designing buildings with light shafts depending on their ability to facilitate air change in these confined outdoor spaces.

2 Methods

2.1 Principles and fundamentals

The architectural configuration of a building with a light shaft impact on fresh air distribution has been assessed using the concept of air change efficiency (Sandberg, 1981; Hang et al., 2009a, 2009b). This theoretical concept relates the residence time of the air volume in a known domain due to the spatial path followed by with the minimum calculated time for an ideal-estimated flow rate (Chen et al., 1969). Given the complexity of conducting field experiments and the evaluation of the age of the air with the then current tracer gas techniques (Sandberg and Sjöberg, 1983), the numerical evaluation of different computation fluid dynamics (CFD) cases was validated using a wind tunnel (Meroney et al., 1999). The wind tunnel experiences have successfully recreated scaled field experiments in real urban environments (Sharples and Bensalem, 2001). These experiences, which set up a reference validation model using a cubic-scale building, allowed the evaluation of some aerodynamic parameters involved in the outdoor ventilation process (Padilla-Marcos et al., 2016a). Those parameters are velocity, turbulence, momentum, and energy of the air displaced by the wind and they relate building shape to its ability to promote the outdoor air change in the immediate environment of the building. Then, it was applied to a full urban model containing complex buildings with light shafts in order to evaluate what occurs inside them and finally it was applied to the "age of the air" concept.

The analysis of the age of the air in a computational model provides information related to the mean residence time of the air circulating in the volume of the model (Sherman et al., 2012). This requires dimensionally defining the extension of the domain, which is limited in relation to the parameter of interest. The analysis of the air change efficiency index demands setting a control domain limiting the urban volume within a larger computational domain ruled by the criteria defined by other studies (Shao et al., 1993) and which is fully developed in a conceptual methodology for this kind of analysis (Padilla-Marcos et al., 2015).

2.2 Outdoor air change efficiency

Indoor spaces are naturally ventilated by taking air from outdoors (Ok et al., 2008). Exhaust air which has been used inside the building can circumstantially be discharged to outdoor spaces (SeppĘnen, 2008). Due to a lack of sufficient air exchanged in outdoor spaces, the indoor ventilation process is carried out with partially polluted air as a result of progressive contamination process by environmental agents and others. Although outdoor air is exposed to a flow of "fresh" air which eases the air change, it may happen that the air distribution was not performed properly throughout the areas where the air exits from the domain volume without a complete mixing.

It has been proved that the air change distribution in confined outdoor spaces depends on numerous factors related to the site, the architectural shape, and the mesh of the urban environment. The overall quality of the air supplied indoors to foster ventilation is directly dependent on this distribution. The quality is evaluated by the concept of air change efficiency (Padilla-Marcos et al., 2016a).

The air change efficiency ratio has been widely developed to assess the air change quality indoors. It is the relation between the time it takes "fresh" air to perform the air change and the minimum flow necessary to achieve it (Eq. (1)). The efficiency index (ε^{a}) analyzes the air change quality unlike the age of the air (τ), which analyzes its quality:

$$\varepsilon^{\mathrm{a}} = \frac{\tau_{\mathrm{e}}}{\tau_{\mathrm{r}}} = \frac{V}{2Q\langle\overline{\tau}\rangle} \le 1, \tag{1}$$

where τ_{e} is the minimum air change time (s); τ_{r} is the exchange time (s); V is the volume of air (m^3); Q is the air change flow rate (m^3/s).

The mean age of the air is the concept by which the average time which a set of air particles takes to traverse the paths followed in a domain is analyzed. The mean residence time of the set of air particles in the domain ($\langle\tau\rangle$) determines the mean exchange time:

$$\overline{\tau}_{\mathrm{r}} = 2\langle\overline{\tau}\rangle, \tag{2}$$

$$\overline{\tau} = \frac{\sigma^2 + \tau_{\mathrm{t}}^2}{2\tau_{\mathrm{t}}}, \tag{3}$$

where σ^2 is the variance of the air distribution function in the domain (s^2), and τ_{t} is the mean time in the surface plane in the outlet (s).

The minimum air change time (τ_{e}) calculates the time the volume of air in a known domain takes to be changed with the flow rate of air running through:

$$\tau_{\mathrm{e}} = \frac{V}{Q}. \tag{4}$$

The air change efficiency index evaluates the ability of the architectural design to facilitate the natural air change, a factor that implies an important energy impact. The higher the efficiency, the more the quality of the exchange increases, but it does not cause an increase of the air quality, which can be partly assessed by the age of the air. An adequate air change in a given domain is guaranteed when the efficiency approaches the perfect mix value, estimated at 50%.

2.3 Outdoor air flow

The flow which promotes air change in an open model was evaluated as a result of the dynamic action of the wind (Hung and Chow, 2001). This action, initially parallel to the ground floor, is affected in the

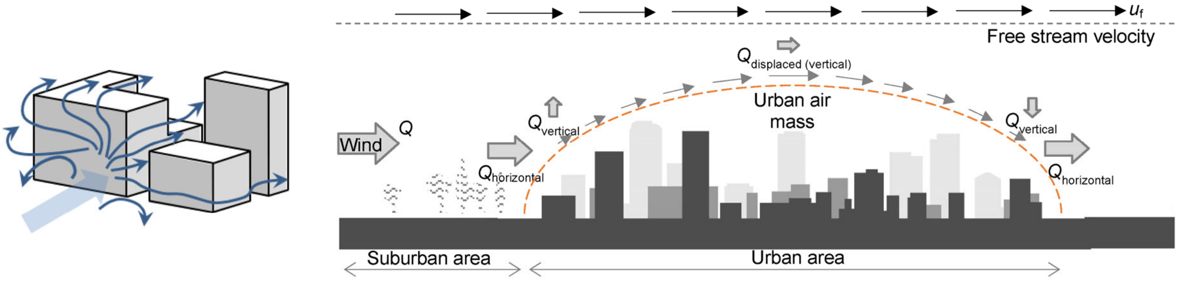

Fig. 1 Outdoor air flow in urban areas

urban environment by friction with building envelopes and the ground, as well as the internal viscosity of the air. This phenomenon produces an urban fully-developed wind profile, especially defined by the free stream velocity (u_f) in which the air flow reaches a pure horizontal component (Fig. 1). Within the urban area, the air flow displaced by the wind changes its directional component due to collision with both the urban mass of air that has been slowed down and the buildings, causing flows in the three perpendicular axes of displacement.

The scaled experiments carried out in the wind tunnel required the adaptation of the real wind profiles to the experimental conditions. It was also necessary to define some turbulence profiles because of shear stresses produced by the triple similarity condition applicable to such models (Recktenwald, 2009):

$$U=\frac{U^*}{K}\ln\left(\frac{z-d}{z_0}\right), \tag{5}$$

$$k_{\text{nw}}=\frac{0.045\rho U_{\text{m}}(\alpha+1)^2}{2\left[\dfrac{U_{\text{m}}h_{\text{t}}(\alpha+1)}{\mu}\right]^{0.25}}, \tag{6}$$

$$k=k_{\text{nw}}+\frac{z}{h_{\text{t}}}\left\{0.002\left[U_{\text{m}}(\alpha+1)\right]^2-k_{\text{nw}}\right\}, \tag{7}$$

$$\varepsilon=\frac{C_\mu^{0.75}k^{1.5}}{Kz},\quad z\le 0.085h_{\text{t}}, \tag{8}$$

$$\varepsilon=\frac{C_\mu^{0.75}k^{1.5}}{0.085h_{\text{t}}},\quad z>0.085h_{\text{t}}, \tag{9}$$

where U is the wind velocity (m/s) at the height z (m); U^* is the friction velocity (m/s); K is the non-dimensional von Karman constant (≈0.41); d is the displacement height for the wind profile (m); z_0 is the roughness height (m); k_{nw} is the turbulent energy close to the model limits due to the wall effect (m^2/s^2); ρ is the air density (kg/m^3) at the temperature of 293.75 K; U_{m} is the mean velocity of the exponential wind profile (m/s); α is the dimensionless exponent for a suburban wind profile; h_{t} is the model height (m); μ is the dynamic viscosity of the air (1.825 ×10^{-5} N·s/m^2 at the temperature of 293.75 K); k is the turbulent kinetic energy (m^2/s^2); ε is the turbulence dissipation rate (m^2/s^3); C_μ is an empirical constant (determined by Launder and Spalding (1974) with an approximate value of 0.09).

The equivalent air flow for a control domain ($\bar{Q}$) within a larger computational domain, whose boundary condition for the inlet is defined by a logarithmic wind velocity profile (Fig. 2), can be obtained by its perpendicular projection (surface y-z):

$$\bar{Q}=Q=\frac{U^*}{K}(y_2-y_1)\left\{\left[z\ln\left(\frac{1}{z_0}\right)\right]_{z_1}^{z_2}+\left[z\ln(z)-z\right]_{z_1}^{z_2}\right\}. \tag{10}$$

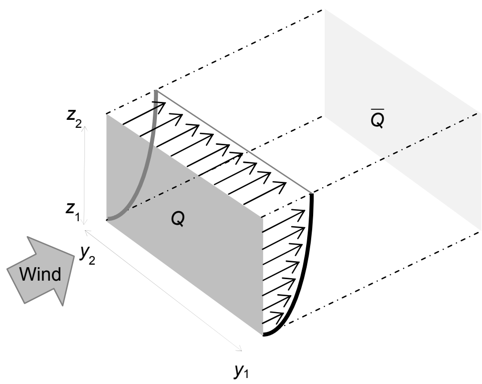

Fig. 2 Equivalent outdoor air flow in the control domain

2.4 Methodology

It was necessary to consider multiple factors, which alter the air flow in the built environment, in order to evaluate the air change inside light shafts. Those factors are analyzed using a new methodology to properly represent the air behaviour inside and outside the light shaft. A control domain which allowed comparative assessment of different cases was established following urban fluid dynamics criteria. The boundary conditions, which intervened in the behaviour of the air and are a consequence of the results from scaled wind tunnel experiences, were set. Then the validation of the CFD simulation models, employing the wind tunnel laboratory experiences, was defined. A catalogue of architectonical cases to be evaluated was considered in order to obtain the patterns which served to define the conclusions that stem from the outcomes.

2.5 Control domain

The application of the air change efficiency concept in outdoor spaces requires a control domain definition, which is able to delimit the air volume to be analyzed. Outdoor spaces are difficult to delimit in the way of an indoor domain. A control domain virtually delimits the outdoor air volume close to the building in an upper domain. The control domain enables assessment of the air behaviour in the immediate surroundings of the building and its aerodynamical influence over its distribution inside the light shaft, avoiding consideration of all the computational domain, which is not an affordable proposition.

The definition of a specific control domain was necessary for each group of cases to be evaluated. The control domain was defined according to the dimensional variations of the architectonical case. An exhaustive study was conducted by Padilla-Marcos et al. (2016a) in which a method for the definition of an ideal control domain for a building with light shaft cases was established based on a single dimensional module. The building width parameter (c_r) was chosen as it was a fixed dimensional parameter among the case studies in order to be able to comparatively analyze the results (Fig. 3). The reference parameter chosen answered the demand for a dimensional module which promoted the definition of an ideal control domain as developed in previous studies. This allowed the assessment of the air change efficiency of the air contained in the light shaft delimiting its opening surface and assuming that the continuity condition for the flows was fulfilled.

A resulting control domain, whose accuracy was tested for all the case studies, was established, measuring 72 m length, 52 m width, and 52 m height. This domain was sized to cover the biggest analyzed building with a square light shaft up to 12 m sideways and 42 m high.

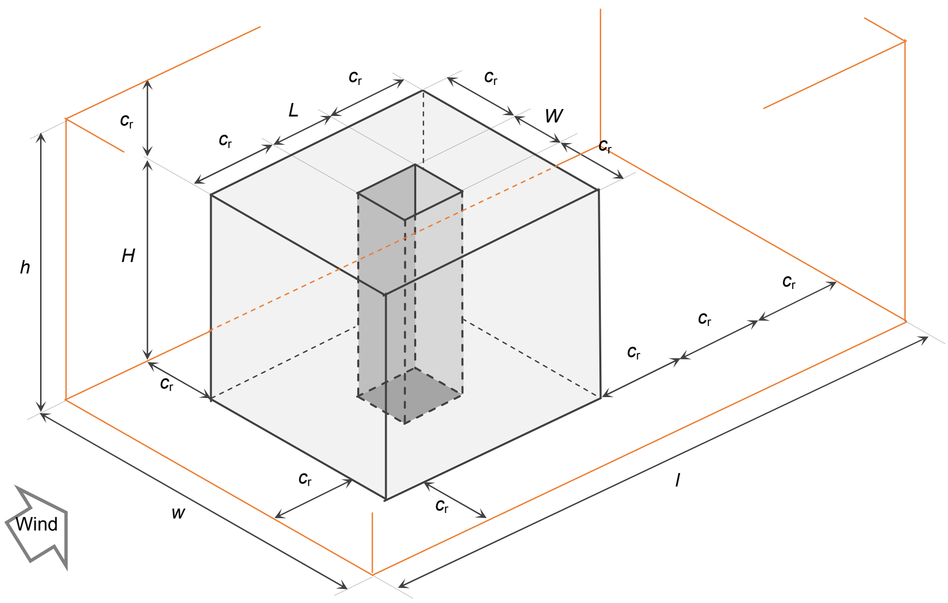

Fig. 3 Dimensions of the control domain (*l*, *w*, *h*) defined according to the dimensions of the building containing a light shaft (*L*, *W*, *H*)

2.6 Boundary conditions

The computational domain was configured recreating the boundary conditions for the application of the physical principles which rule the aerodynamics inside the experimental wind tunnel in isothermal conditions: continuity, momentum, velocity distribution, viscosity, turbulence, etc.

The computational domain encompassed a wind tunnel section in which the side limits enclosing the air were established (Fig. 4). The air exhausts and supplies were placed at the ends of the wind tunnel section physically defined by the velocity and turbulence profiles (Eqs. (5)–(9)). The sidewalls of the computational domain were defined as low roughness airtight surfaces (Table 1).

Table 1 Boundary conditions

Item	Description
Air characteristics (fluid)	
Model height, H (m)	25.000
Air density (kg/m^3)	1.204
Temperature (K)	293.751
Reynolds number	37 250
Kinematic viscosity (m^2/s)	1.515×10^{-5}
Dynamic viscosity (N·s/m^2)	1.825×10^{-5}
Inlet boundary conditions	
Reference velocity (m/s)	6.000
Reference height (m)	100.000
Turbulence energy	Eqs. (6) and (7)
Turbulence dissipation	Eqs. (8) and (9)
Turbulence height (m)	64.000
von Karman constant	0.41
Wall conditions	
Roughness height (m)	0.000
Displacement height (m)	0.000
Temperature (K)	293.751
Side and upper walls	Following boundaries without symmetry
Isothermal floor boundary conditions	
Exponential law	0.22
Friction velocity (m/s)	0.350
Roughness height (m)	0.080
Displacement height (m)	0.000

2.7 CFD validation and configuration

The computational domain was established as a regular half-mesh of up to 2.5×10^6 cells, with a refinement regime near the built limits following accepted criteria (Franke et al., 2007). As previously described by Padilla-Marcos et al. (2016b), a cell refinement near the walls (y+) is achieved reaching a value close to 20.

The cases were simulated using CFD numerical calculation methods with the ANSYS Fluent 15.0© tool, following the equations which define the wind velocity profiles and the energy and turbulent dissipation profiles for the urban wind (Eqs. (5)–(9)).

Three models of turbulence, standard k-ε (SKE), re-normalization group (RNG), and realizable k-ε (RKE) (Shih et al., 1995), were used to verify their affinity with the results of the CFD validation model. In particular, these turbulent models with standard wall functions (SWF) were applied to include the wall effect: SKE model and RNG model, developed by Yakhot and Orszag (1986) and Murakami and Mochida (1988). The suitability of the RNG models was also verified by applying the enhanced wall treatment (EWT) method for handling the wall effect (Shih et al., 1995).

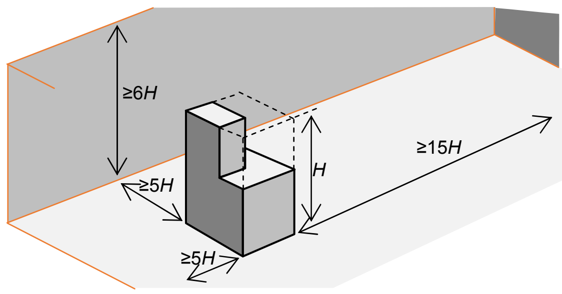

Fig. 4 Proportions of the computational domain defined by the building dimensions

The experimental results from the CEDVAL project of Universität Hamburg, Germany were used in the validation of the numerical configuration. The CEDVAL project (http://mi-pub.cen.uni-hamburg.de/index.php?id=432) provides the experimental results of diverse real cases in a public database giving the boundary conditions used in a BLASIUS wind tunnel (Fig. 5).

The validation was split into two phases. The first one evaluated the CFD configuration of the velocity and turbulent wind profiles with the boundary conditions used in urban environments (Fig. 6). The second phase of the validation stated the suitability of the configuration in its application over complex urban models with confined outdoor spaces such as courtyards and light shafts.

Initially, the first stage of the validation process, conducted in the BLASIUS wind tunnel (Table 2), consisted of 8 cases (V1–V8), which were carried out following the aim of adjusting the parameters dependent on the experimental model A1-4 (Fig. 7). The

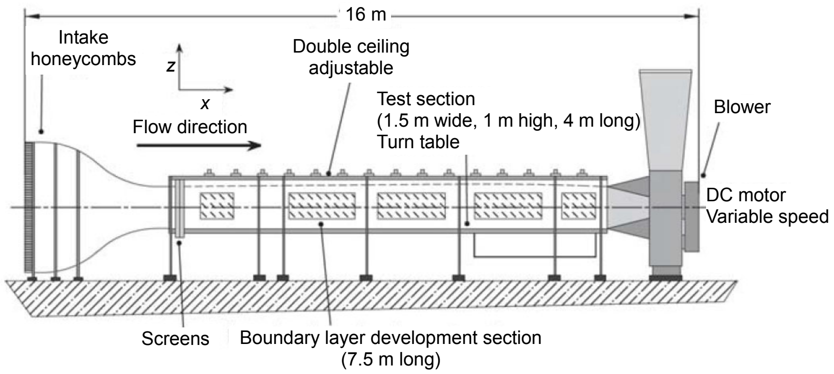

Fig. 5 BLASIUS wind tunnel (Leitl and Shatzmann, 1998)

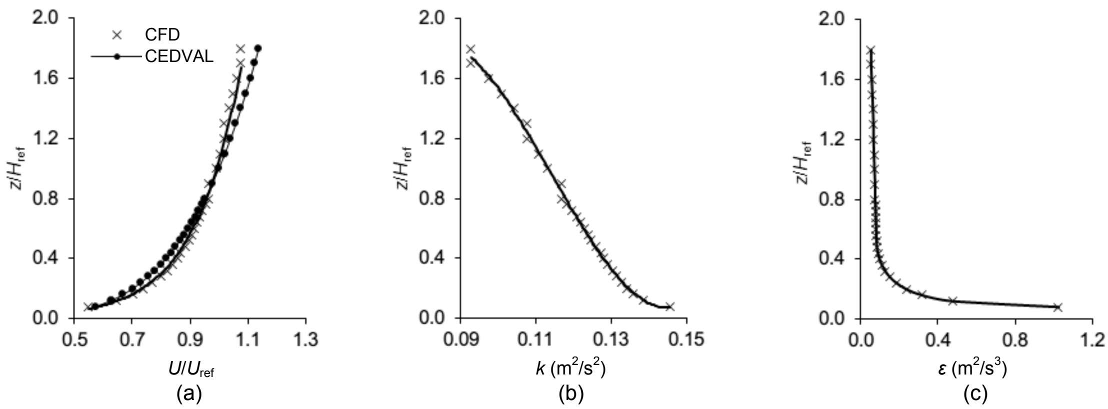

Fig. 6 Urban wind velocity (a), turbulent kinetic energy (b), and turbulent dissipation rate (c) profiles (validation-first phase)

H_{ref}: reference height; U_{ref}: reference velocity

Table 2 Average deviations of the results in the first 8-case validation phase

Case	Variation assessed	In plane "*xy*"			In plane "*xz*"		
		TMD (%)	MDS (%)	MDA (%)	TMD (%)	MDS (%)	MDA (%)
V1	Inlet turbulent intensity 20%	5.95	−5.07	32.67	5.93	3.16	33.90
V2	Suction model	−167.53	−159.33	47.19	−161.32	−158.96	45.90
V3	Smooth wall limits	4.34	−6.38	33.53	3.79	1.69	35.34
V4	Inlet turbulent profile	2.26	−3.81	20.04	−4.29	−2.74	18.36
V5	Ground free wall-rough effect	4.99	−1.08	22.27	−0.21	1.84	20.91
V6	No-turbulence profile in "pressure outlet"	4.77	−6.00	33.46	4.29	2.09	35.35
V7	Turbulence profile in "pressure outlet"	4.77	−6.00	33.46	4.29	2.09	35.35
V8	"Symmetry" boundaries in tunnel walls	4.34	-6.37	33.53	3.79	1.69	35.34

TMD: total mean deviation; MDS: mean deviation of horizontal velocities; MDA: mean deviation of absolute velocities

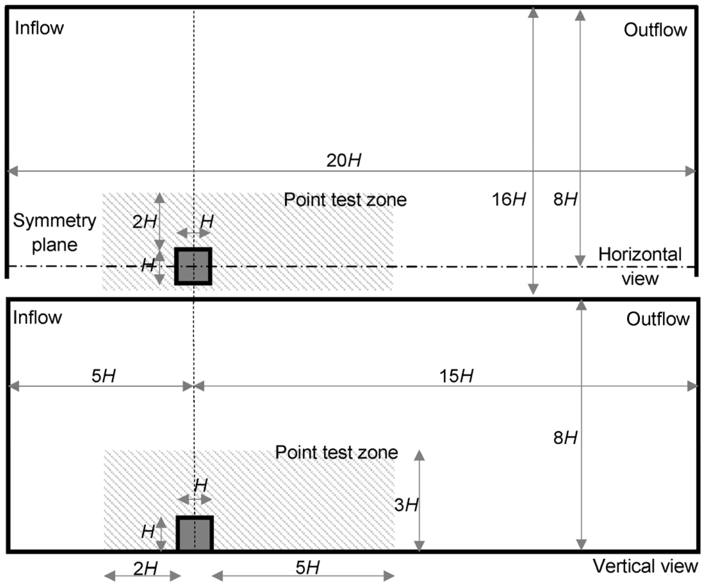

Fig. 7 First stage of the validation process: single cubic building

adjustment of the parameters in each validation process consisted of evaluating the results' accuracy related to the experimental reference case in the wind tunnel. The 8-case evaluation developed the CFD model by assuming different options defined by other recognized authors.

The validation sequence provided information about possible CFD configurations taken from laboratory conditions. Measured deviations over two perpendicular surfaces were evaluated. The total mean deviation (TMD) considered all the horizontal velocities with a parallel component to the main wind direction (x axis). The mean deviation of horizontal velocities (MDS) in the immediate surroundings was obtained by measuring points at a distance <2.5H from the building model. The mean deviation of absolute velocities (MDA) in the building surroundings was <2.5H from the building model.

According to the eight completed validation processes, it was established that differing from the experimental model, the simulations required the definition of the turbulent profiles at the inlet, and this discarded the use of suction models. The most accurate results were reached by means of the use of turbulent models (Table 3).

The second phase used the B1-2 model of the CEDVAL project (Fig. 8), verifying its results in more than 650 sample points (Table 4). A deviation less than 4% on the velocities along with the wind direction (x velocity) was achieved. The mean

Table 3 Accuracy obtained from CFD model (validation-first phase)

Model	Mean deviation (≤2H) (%)	Mean of local deviations (%)
SKE-SWF	−19.26	−11.97
RNG-SWF	−3.81	3.72
RNG-EWT	7.20	2.97
RKE-EWT	7.56	2.57

SKE: standard k-ε; SWF: standard wall functions; RNG: re-normalization group; EWT: enhanced wall treatment; RKE: realizable k-ε

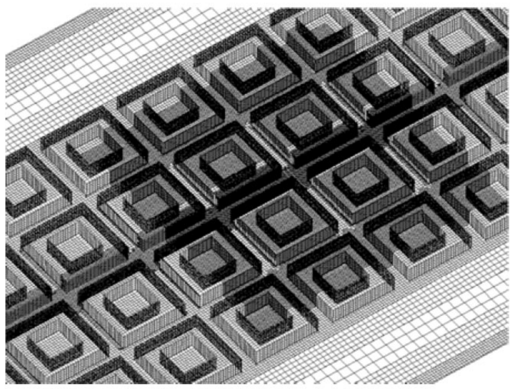

Fig. 8 Second stage of the validation process: complex urban model with outdoor spaces

accuracy of the results in the wind velocity magnitude was greater than 95%. It was verified that the RKE-EWT turbulence model showed the most precise results (Table 4). Table 5 shows the repetition of the velocity results which were obtained in the validation tests.

Table 4 Accuracy of the results of the urban model validation

CFD method	Deviation (%)			
	Velocity magnitude (U)	x velocity	y velocity	z velocity
RNG-SWF	±4.57	±3.12	±7.35	±9.34
RNG-EWT	±11.19	±3.12	±7.35	±9.35
RKE-EWT	±3.68	±2.01	±12.46	±4.23

Table 5 Repetition on velocity validation results

Result	Percentage (%)		
	RNG-SWF	RNG-EWT	RKE-EWT
<5%	15.84	2.92	12.43
5%–10%	29.90	3.57	31.07
10%–20%	22.57	8.12	23.82
>20%	31.69	85.39	32.69

2.8 Case study

The impact of dimensional parameters involved in the architectonical design of the buildings with a light shaft on the air change efficiency was assessed. It was developed in a sequence of cases in which the light shaft and the building dimensions varied, depending on the built region surrounding the light shaft determined by its building width (c_r) (Fig. 3). These cases were analyzed according to different wind velocity conditions in the urban environment. This allowed the analysis of the air behaviour in the light shaft due to the influence of the air change flow in its opening. The air change efficiency values in intermediate cases were obtained by a similar manner through geometric interpolation. Moreover, 220 cases were numerically simulated under the fixed validated conditions and establishing three different control domains depending on the building width dimension as shown in Fig. 3.

The 220 evaluated cases matched buildings with a light shaft whose building width (c_r) varied between 10 and 20 m in 5 m intervals. The light shaft dimensions varied between 2 and 6 m in its horizontal measurements ($L\times W$) in 1 m intervals and between 6 and 42 m in its vertical dimension (H) in 6 m intervals, which coincided with the building total height. Wind velocity was defined for each simulation sequence, varying between 0.75 and 9 m/s (0.75, 1.5, 3, 6, and 9 m/s).

3 Results

From the results (Table 6) it is verified that the greatest impact on the efficiency results is caused by the light shaft length (L), whereas the cross dimension to the wind direction (W) is almost negligible. The conclusion obtained is that when increasing the length (L), while keeping the other geometric variables constant, the driving force becomes relatively strong. However, the cross dimension acquires a significant impact on the analysis of air quality in the light shaft due to the consequent increase in the mean age of the air of the analyzed points. This is partly caused by the chaotic trajectory followed by the air mass in the light shaft and whose detailed analysis will require further analysis.

The analysis of the dimensional variations established in the case studies generates premises that serve as a reference basis for comparative study. It is noted that the lowest efficiency value is obtained in the light shaft with dimensions 6 m×2 m×42 m and a building width of 10 m and a reference wind velocity of 3 m/s. The greatest efficiency value from the analyzed cases is obtained for the case of 6 m×6 m×6 m with 10 m building width and a velocity of 3 m/s. From these results, it is confirmed that the highest variation in efficiency is found in those cases in which the wind velocity is 3 m/s and the building width is 10 m. The assessed cases which comply with these conditions define the baseline of the analysis. Therefore, the reference values of the air change efficiencies in the light shafts vary between 1.06% and 42.62%. The mean efficiencies of the cases with equal rate H/L and the same height vary between 1.69% and 35.76%. These values also correspond to the greater length of the analyzed cases (L=6 m).

Table 6 Ventilation efficiency results of the reference cases

H (m)	W (m)	L=2 m				L=3 m				L=4 m				L=5 m				L=6 m			
		H/L	τ (s)	ε^a (%)	Mean ε^a (%)	H/L	τ (s)	ε^a (%)	Mean ε^a (%)	H/L	τ (s)	ε^a (%)	Mean ε^a (%)	H/L	τ (s)	ε^a (%)	Mean ε^a (%)	H/L	τ (s)	ε^a (%)	Mean ε^a (%)
	2		808	4.53			429	10.38			206	21.28			183	24.38			151	30.03	
	3		735	4.51			378	10.56			160	26.01			132	32.54			110	39.72	
6	4	3.0	703	4.55	4.79 (±1.20)	2.0	344	10.66	10.67 (±0.27)	1.5	151	26.65	26.05 (±4.77)	1.2	129	32.80	31.99 (±7.61)	1.0	101	25.89	35.76 (±9.87)
	5		682	4.35			324	10.81			139	28.01			117	35.32			105	40.55	
	6		577	5.99			306	10.95			133	28.30			115	34.89			95	42.62	
	2		3511	4.38			2241	5.84			1213	9.76			661	16.66			419	24.79	
	3		3254	4.52			1961	6.58			979	12.17			552	20.34			381	28.08	
12	4	6.0	3077	4.65	4.84 (±1.08)	4.0	1762	7.25	7.04 (±1.20)	3.0	922	13.11	12.90 (±3.14)	2.4	533	21.70	21.56 (±4.90)	2.0	234	30.09	28.61 (±3.82)
	5		2973	4.72			1670	7.60			847	14.40			491	24.01			372	30.41	
	6		2520	5.92			1594	7.91			814	15.07			477	25.08			377	29.65	
	2		8628	3.43			6951	2.91			5147	3.21			3647	3.85			2546	4.85	
	3		8249	3.69			6292	3.32			4535	3.70			2915	4.87			1819	6.81	
18	4	9.0	7882	3.97	4.17 (±1.09)	6.0	6036	3.54	3.53 (±0.62)	4.5	4256	4.02	3.94 (±0.73)	3.6	2655	5.44	5.22 (±1.37)	3.0	1555	8.14	7.84 (±2.99)
	5		7154	4.50			5797	3.76			4090	4.26			2521	5.83			1407	9.23	
	6		6258	5.26			5368	4.13			3930	4.50			2445	6.10			1303	10.17	
	2		15668	3.58			13223	2.52			10978	2.26			7232	2.74			6745	2.61	
	3		15101	3.97			12298	2.87			9920	2.63			7822	2.72			5971	3.05	
24	4	12.0	14279	4.47	4.85 (±1.98)	8.0	11868	3.09	3.14 (±0.71)	6.0	9221	2.96	2.94 (±0.68)	4.8	7080	3.15	3.20 (±0.68)	4.0	5377	3.53	3.51 (±0.90)
	5		12497	5.42			11283	3.39			8697	3.27			6578	3.52			4967	3.97	
	6		10297	6.83			10344	3.85			8197	3.59			6184	3.88			4655	4.38	
	2		25187	3.59			21946	2.23			19017	1.82			16213	1.69			13428	1.72	
	3		24367	4.03			20615	2.53			17177	2.16			14054	2.09			11436	2.15	
30	4	15.0	23065	4.59	4.73 (±1.14)	10.0	19690	2.82	2.86 (±0.72)	7.5	15885	2.48	2.47 (±0.65)	6.0	12474	2.50	2.47 (±0.78)	5.0	9821	2.65	2.62 (±0.90)
	5		20138	5.61			18717	3.13			14907	2.79			11450	2.87			8865	3.09	
	6		17702	5.83			17282	3.58			14066	3.11			10737	3.22			8206	3.50	
	2		37180	3.51			33109	2.02			29386	1.55			25905	1.36			22435	1.30	
	3		36113	3.95			31033	2.36			26686	1.86			22382	1.72			18723	1.69	
36	4	18.0	34392	4.47	4.66 (±1.39)	12.0	29956	2.58	2.61 (±0.64)	9.0	24789	2.15	2.13 (±0.58)	7.2	20023	2.06	2.03 (±0.67)	6.0	16239	2.09	2.06 (±0.76)
	5		30401	5.33			28715	2.86			23468	2.42			18580	2.37			14758	2.45	
	6		25732	6.05			26855	3.25			22426	2.68			17658	2.64			13811	2.77	
	2		51581	3.39			46687	1.85			42118	1.37			37887	1.16			33749	1.06	
	3		50314	3.79			44156	2.16			38545	1.64			32901	1.47			28111	1.40	
42	4	21.0	46921	4.10	4.32 (±1.00)	14.0	42738	2.37	2.40 (±0.56)	10.5	36037	1.90	1.89 (±0.52)	8.4	29859	1.76	1.73 (±0.57)	7.0	24817	1.72	1.69 (±0.63)
	5		43201	5.00			41274	2.63			34473	2.14			28163	2.01			22960	2.00	
	6		37482	5.32			38971	2.96			33349	2.36			27109	2.23			21847	2.24	

U=3 m/s; c_r=10 m

The reference results allow us to relate the air change efficiencies to the mean age of the air inside the light shaft. It makes sense thinking that the mean ages in the light shafts increase when the efficiency decreases. So it does when increasing H/L, in other words, when increasing the height of the light shaft (H).

Taking the results for the precedent conditions as a reference, the efficiency values and the mean age of the air in relation to the rate H/L are represented, omitting the cross dimension (W) (Fig. 9). The omission supposes a reduced impact on the efficiency results. In Fig. 9, the trend followed by the efficiency, with regard to the H/L ratio for the reference criteria, is observed.

Fig. 9 shows the relationship between the mean age of the air (dark grey) and the air change efficiency (light grey) inside the light shaft related to the ratio H/L, which is the proportion of the light shaft by each height (H). It can be said that the accuracy of the results of the air change efficiency is better when the light shaft is higher, demonstrating that there is a pattern which describes the behaviour of the air inside the light shaft as a confined outdoor space. The mean age of the air qualifies the air volume inside the confined outdoor space and the efficiency value indicates how the quality is distributed within the volume.

An identical operation is carried out for the cases in which the building width (c_r) and the wind velocity (U) vary. When analyzing the trend of the results with these settings, it is found that there is no clear direct relationship between the obtained efficiencies and the average ages of the air acquired (Fig. 10), whose patterns are described in Fig. 9.

Fig. 10 shows how the air change efficiency inside the light shafts is affected when the building width (c_r) and the wind velocity (U) are reconsidered as reference parameters. The age of the air patterns maintains the trends and the efficiency improves when the building width (c_r) grows.

Efficiency patterns can be established by means of approximating the trend curves of the results set to geometric functions, taking into account the tolerances of the average values indicated in Table 6. The results obtained are numerically related in a single power-law equation dependent on the H/L rate, the wind velocity (U), and the building width (c_r):

$$
\begin{aligned}
&\varepsilon^{\mathrm{a}} \approx AU^{B},\\
&A = a_1\left(\frac{H}{L}\right)^3 + a_2\left(\frac{H}{L}\right)^2 + a_3\frac{H}{L} + a_4,\\
&B = b_1\left(\frac{H}{L}\right)^3 + b_2\left(\frac{H}{L}\right)^2 + b_3\frac{H}{L} + b_4,\\
&a_1 = 27.7610\times10^{-6}c_{\mathrm{r}}^2 - 746.1995\times10^{-6}c_{\mathrm{r}}\\
&\quad + 3308.9509\times10^{-6},\\
&a_2 = -483.3086\times10^{-6}c_{\mathrm{r}}^2 + 13209.5303\times10^{-6}c_{\mathrm{r}}\\
&\quad - 55550.9142\times10^{-6},\\
&a_3 = 2511.5713\times10^{-6}c_{\mathrm{r}}^2 - 70284.8286\times10^{-6}c_{\mathrm{r}}\\
&\quad + 265536.9800\times10^{-6},\\
&a_4 = -4127.2866\times10^{-6}c_{\mathrm{r}}^2 + 125279.8867\times10^{-6}c_{\mathrm{r}}\\
&\quad - 370282.4851\times10^{-6},\\
&b_1 = -225.5772\times10^{-6}c_{\mathrm{r}}^2 + 5530.7798\times10^{-6}c_{\mathrm{r}}\\
&\quad - 33348.6580\times10^{-6},\\
&b_2 = 4105.9026\times10^{-6}c_{\mathrm{r}}^2 - 100415.7198\times10^{-6}c_{\mathrm{r}}\\
&\quad + 604354.4288\times10^{-6},\\
&b_3 = -23125.3344\times10^{-6}c_{\mathrm{r}}^2 + 561637.8005\times10^{-6}c_{\mathrm{r}}\\
&\quad - 3378820.5943\times10^{-6},\\
&b_4 = 41557.1159\times10^{-6}c_{\mathrm{r}}^2 - 1034556.2929\times10^{-6}c_{\mathrm{r}}\\
&\quad + 5926885.6022\times10^{-6}.
\end{aligned}
\tag{11}
$$

The suitability of the proposed Eq. (11) with parameters for wind velocity (U) ranges between 0.5 and 6.0 m/s and building widths (c_r) between 10 and 20 m is numerically checked.

4 Discussion

The analysis of the quality of the air change, by means of the concept of the air change efficiency in the light shaft, allows cataloguing of the design of this confined outdoor space according to the ventilation needs in the indoor spaces which open onto it.

The complexity of the aerodynamic analysis in urban environments and the variables involved require the definition of simplified strategies for the architectural design in order to achieve efficient ventilation. The variables, i.e. dimensions of the light shaft (L, W, H), wind velocity (U), and building width

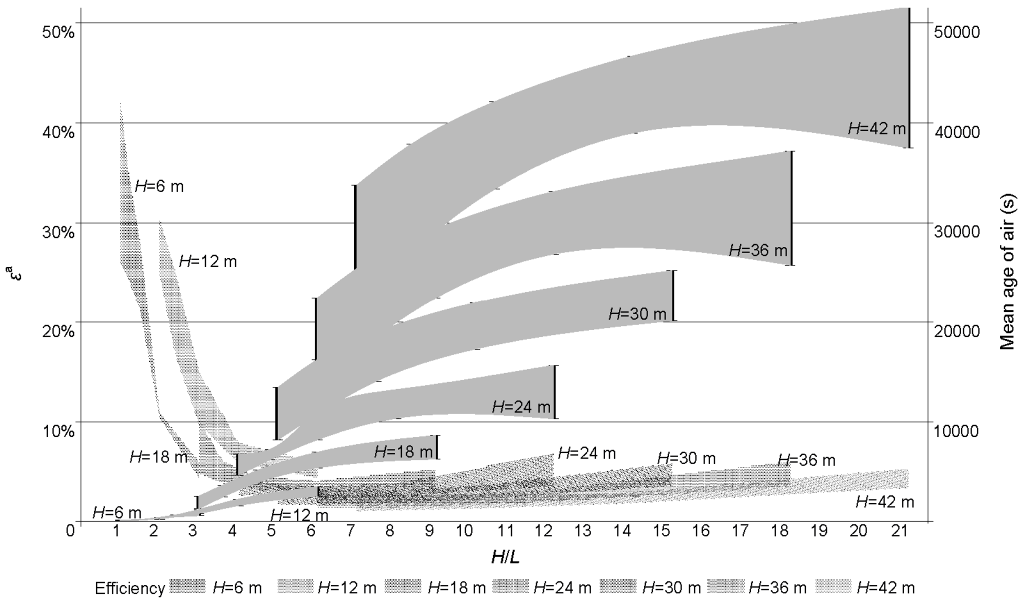

Fig. 9 Reference curves for the efficiency and the age of the air results

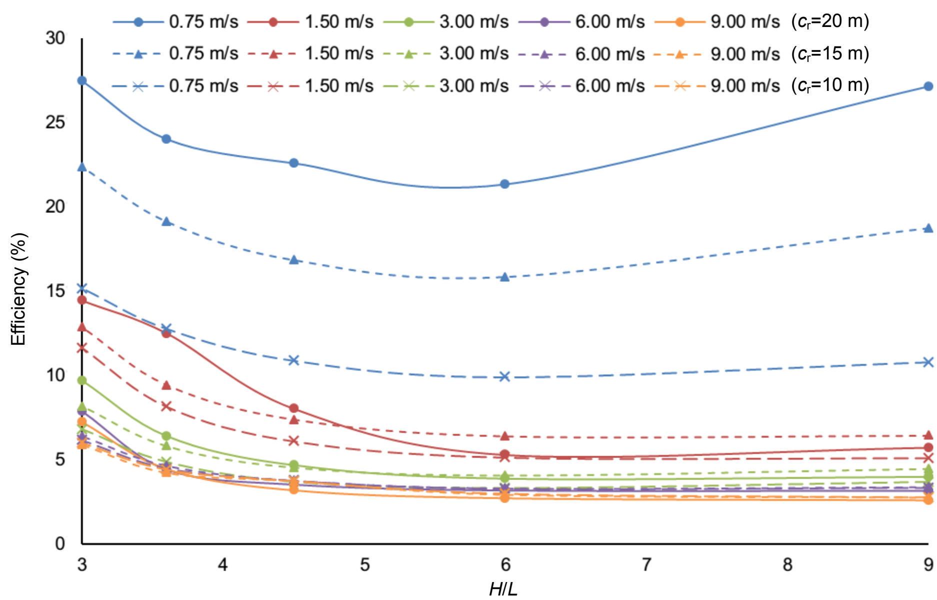

Fig. 10 Efficiency results with varying wind velocities (U) and building widths (c_r)

(c_r), are in turn combined to evaluate their impact on the behaviour of the air contained in the light shaft to originate its renewal by means of the exchange with the outside air.

To achieve the design patterns of the light shafts according to their air change ability, it has been decided to simplify the different intervening variables. As an architectural design strategy these variables provide a numerical model application. Thus, the impact that the design and the environment of the building with a light shaft have on the air change efficiency is determined.

According to the results obtained for the evaluated cases, it seems logical to outline light shafts with heights up to 12 m. However, the residential spaces more susceptible to the air quality (like bedrooms and living rooms) must be opened for indoor ventilation purposes only in the upper half of the light shafts with a height of less than 24 m and in the first 12 m from the top in the rest of light shafts. This would be possible if only two of the facing enclosures of the light shaft were perpendicularly separated by at least 5 m. This dimension can be reduced to 4 m when the openings are vertically separated by a distance of less than 6 m from the top of the light shaft.

5 Conclusions

The purpose of this study was to find a simplified method to serve as a tool for technical designers of buildings with a light shaft. This method serves to define the design strategies regarding the consideration of the light shafts as valid outdoor spaces for the indoor ventilation according to their capacities. Several countries consider these confined outdoor spaces as places to ventilate the indoor spaces, a fact which can lead to a serious problem if their design and dimensions are not considered.

Numerically, there is a remarkable reduction of the air change capacity in these outdoor spaces confined by the adjacent buildings. This is demonstrated with reference to the ability of air change which other types of outdoor spaces have. The capacity for the air change, by means of the concept of efficiency, has been numerically analyzed, as well as the air "aging" by means of the mean age of the air. It can be concluded that, with the criteria established in this study, these spaces are not healthy enough for indoor ventilation; however, and comparatively, the light shafts whose H/L ratio is less than 3 present interesting capacities to produce air change. These light shafts, as well as providing good air change efficiencies, cause a slight aging of its air mass, which indicates that they offer the best results of the analyzed cases.

The conclusions are based on the outcomes obtained from the evaluation of 220 cases in isothermal conditions and in a single perpendicular wind direction to the building. Further research must be done to clarify the results exhibited here and to provide general conclusions applicable to other cases.

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中文概要

题　目：利用采光井进行建筑通风的新型应用模型：基于案例研究评估的建议

目　的： 1. 探究如何在有限的室外空间下简便地计算换气质量；2. 建立利用采光井进行建筑通风的应用模型。

创新点： 1. 案例研究评估的成熟方法论应用；2. 得到采光井对室内空气通风促进度的速算图表。

方　法： 1. 采用风洞分析的两步确认法；2. 对实际采光井模型进行计算流体动力学应用。

结　论： 1. 高长比小于 3 的采光井表现出了不错的换气能力；2. 对空气质量要求更高的居住空间（如卧室和起居室）而言，室内通风口必须被设在高度低于 24 米的采光井的上半部分或者其他采光井中距离顶部 12 米以内的位置。

关键词： 室外空气质量；采光井；自然通风；计算流体动力学；换气效率