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GUÍAS DE DISEÑO PARA EL USO DE INTERCAMBIADORES DE VIENTO EN UNA EDIFICACIÓN CON UNA VENTANA A BARLOVENTO O A SOTAVENTO

DESIGN GUIDELINES FOR THE USE OF WINDEXCHANGERS IN A BUILDING WITH A WINDOW TO WINDWARD OR TO LEEWARD

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RESUMEN

Este trabajo presenta guías de diseño para el uso de intercambiadores de viento en el techo en edificaciones con una ventana a barlovento o a sotavento, para diferentes escenarios dependiendo de la orientación de la ventana y de la diferencia de temperatura entre el aire exterior y el aire interior. Estas guías de diseño son resultado de un estudio experimental. Comúnmente en la literatura los intercambiadores de viento son conocidos como captadores de viento (windcatchers en inglés), estos son pequeñas estructuras ubicadas sobre el techo de las edificaciones. El nombre de intercambiador de viento; explica el hecho de que esta estructura puede actuar como un inyector o extractor de aire, dependiendo de la combinación de orientaciones de las aberturas de éste y de la ventana en la edificación. En este trabajo se presentan los principales resultados experimentales obtenidos en una edificación conformada por un cuarto a escala 1:25. En total se estudiaron 24 casos, 12 casos por cada orientación de la ventana. Como caso base de comparación se utilizó el mismo cuarto sin intercambiador de viento para cada una de las dos orientaciones de ventana. Los experimentos se llevaron a cabo en un canal de agua, donde se generó la capa límite atmosférica y un sistema de visualización por imágenes de partículas estereoscópico para medir el campo de velocidades con tres componentes en el plano central. Los parámetros utilizados para evaluar el desempeño de la ventilación son el flujo volumétrico a la habitación, dado por los flujos a través de la ventana y de la conexión al intercambiador de viento, y el porcentaje de área con una magnitud de velocidad significativa en el plano central. El análisis de estos resultados muestra que el uso de un intercambiador de viento puede incrementar hasta 4 veces el flujo volumétrico y al menos duplicar el porcentaje del área con magnitud de velocidad significativa.

ABSTRACT

This paper presents design guidelines for the use of windexchangers on the rooftop in buildings with a window to windward or leeward, for different scenarios depending on the orientation of the window and the temperature difference the outside air and indoor air. These design guidelines are the result of an experimental study. Commonly in the literature, the windexchangers are named as windcatchers, these are small structures located on the building rooftop. The name windexchanger explains the fact that the same structure can act as injector or extractor of the air, depending on the combination of the openings thereof with the building window. The experimental results of a building conformed by a single room scaled to 1:25 are presented. A total of 24 cases were studied; 12 for each window orientation. The rooms without windexchanger and with both window orientations were used as baseline cases for comparison. The experiments were performed in an open water channel, where an atmospheric boundary layer and a stereo-particle image velocimetry to measure velocity vector field with three components in the central plane were reproduced and installed, respectively. The used parameters to evaluate the ventilation performance are the flow rate into the building through the window and the interconnection with the windexchanger and the area percentage with a significant velocity magnitude in the central plane. The result analysis shows that the use of a windexchanger can increase four times the flow rate and at least duplicate the area with significant velocity magnitude.

Keywords: Natural ventilation; Windexchanger; Windcatcher; Experiments; Water channel; SPIV; Leeward window; Windward window.

INTRODUCTION

Natural ventilation is used not only for maintaining the indoor air quality, but also for thermal comfort, for this purpose the airflow distribution inside the building becomes relevant. Hence, the generation of knowledge about the airflow distribution in a building is important. That airflow inside a room can be increased with the use of cross-flow ventilation, that produced by two openings, one at windward and the other at leeward (Karava et al., 2011). Nevertheless, when the building design imposes limitations to use this strategy, and the roof of the room is part of the envelope, the use of a windexchanger on the rooftop is an alternative. The term windexchanger has been proposed by Cruz-Salas et al. (2014) for a small structure based on the building roof, which promotes natural ventilation. This structure is commonly referred in the literature as windcatcher (Montazeri, 2011). The new name accounts for the fact that this structure can act as an injector or extractor of air, depending on orientation when the room has another opening (Cruz-Salas et al., 2014), or acts simultaneously as an injector and extractor when the room has no other opening (Li and Mak, 2007).

The present study was inspired by low-income houses constructed in Mexico, which represented 58% of a total of 560,368 offered houses in 2014 (SEDATU, 2015). In general, these houses have no air-conditioning installations, moreover, they have not been properly designed for natural ventilation (Huelsz et al., 2011), which is an important issue in hot-humid climates (Givoni, 1981). Therefore, the improvement of natural ventilation in that type houses by constructing the windexchanger will represent a high impact for the hygrothermal comfort of the occupants and for energy savings (Oropeza-Perez and Ostergaard, 2014). Additionally, the windexchanger will cost a low percentage of the total cost of the low-income houses, as well as the installation will not require specialist technicians.

Guidelines for the use of windexhangers in a room with a window both windward and leeward façade and a windexchanger at the rooftop were set in accordance with the experimental results reported by Cruz-Salas et al. (2014) and Castillo et al. (2015). The guidelines are derived from a systematic analysis of the different flow behaviors a windexchanger in a room with a window presents. In addition, the present study summarizes the experimental results reported in Cruz-Salas et al. (2014) and Castillo et al. (2015). These studies provide experimental velocity data obtained with a stereoscopic particle image velocimetry (SPIV) system, which gives information about the airflow inside the room. The distribution of the airflow inside the room becomes relevant when ventilation is used not only for maintaining indoor air quality, but also for hygrothermal comfort especially in hot climates. The guidelines presented in this work are expected to be useful to constructors and designer in order to enhance natural ventilation in houses already built or to be built in hot climates, particularly for low-income houses.

EXPERIMENTAL SETUP AND METHODOLOGY

The experimental setup is composed of an open water channel, the models, and a SPIV measurement system. The water channel has a length of 6.00 m, height of 0.50 m, and width of 0.31 m. The test section has a length of 1.00 m, beginning at 4.0 m from the water inlet (Fig. 1). At the inlet, the channel has a settling chamber to reduce transverse and vertical turbulence intensity and velocity differences. A curved ramp is placed at the end of the channel to maintain a constant water depth of 0.41 m and to reduce the water outlet influence on the test section. The models (Fig. 2a), in scale 1: 25, consist of two parts. The first part is a room with no roof and a window in one of its walls. This part was used in all the experiments. The second part is interchangeable and consists of the roof with or without windexchanger.

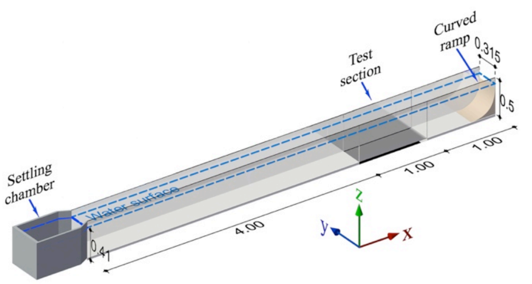

Figure 1: Perspective view of the water channel with dimensions, units in meters.

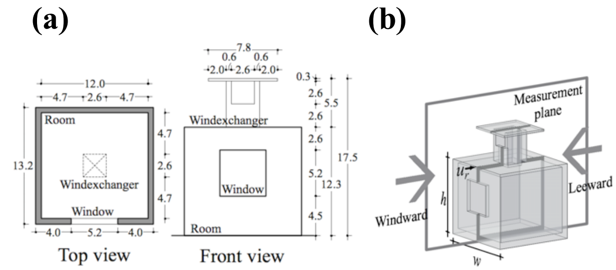

Figure 2: Model of the room with one of the windexchangers. (a) Top and front view, units in centimeters; (b) Isometric view with the measurement plane and flow direction, where h = 0.123 m is the room model external height and w = 0.132 m is the width.

This second part can be rotated to achieve different orientations of the windexchanger with respect to the flow direction. The models were made of transparent acrylic. The room model represents a full-scale room with an internal area of 3.00 m × 3.00 m and an internal height of 2.70 m, having a square window, 1.30 m wide, centered on the wall. The base of the window is at a height of 0.90 m above the floor level. All windexchangers have a height of 1.40 m measured above the rooftop level, and have a square cross section of 0.65 m in length.

A SPIV system was used to measure the three velocity components on the central plane of the flow (Fig. 2b). The system is composed of a twin-cavity Nd-YAG laser with integrated optics for a light sheet output, two digital high-resolution cameras and a high-precision electronic controller. The control data acquisition and the processing by using the LaVision Davis program were carried out. For each experiment, a total of 110 velocity vector fields were taken with an interval of 0.04 s.

The generation of the vertical velocity profile in the water channel test section corresponding to a small town was achieved by using a set of vertical plates located near the entrance of the water channel (Cruz-Salas et al., 2014). The fit to the experimental data of the velocity profile (Fig. 3a) is given by the power law (Tominaga et al., 2008),

$$u(z) = U_r \left(\frac{z}{z_r}\right)^{\alpha}, \qquad (1)$$

where u is the velocity at height z, U_r = 0.12 m/s is the velocity at the reference height z_r = 0.286 m, and α = 0.251 ± 0.004 is the power-law exponent, which is in the typical range of a small town, from 0.25 to 0.30 (Bañuelos-Ruedas et al., 2010). The average difference between the velocity profiles of the windward cases and leeward is 6%. In Fig. 3b, the vertical profile of turbulent intensity, *I(z),* is presented. It was calculated according (Ramponi and Blocken, 2012),

$$I(z) = \frac{k(z)^{1/2}}{u(z)}, \quad k(z) = \frac{1}{2}\left(\sigma_u^2(z) + \sigma_v^2(z) + \sigma_w^2(z)\right) \qquad (2), (3)$$

where k is the turbulent kinetic energy (TKE), σ_u, σ_v, and σ_w are the standard deviation of velocity in the x, y, and z directions, respectively. For the experiments, dynamic similarity is given by the Reynolds number, $Re = UL/\nu$, where U is the characteristic velocity of the flow, L the characteristic length, and v the kinematic viscosity of the fluid. For these experiments, the relevant Reynolds number is the building Reynolds number Re_b, where L is taken as the external height of the room (h = 0.123 m in the laboratory scale) and U is the magnitude of the velocity in the test section without the room model at h (u_r = 0.094 m/s), giving $Re_b = 1.3 \times 10^4$.

Six types of windexchangers with different orientations with respect to the wind flow are studied, giving eleven cases per each window orientation; i.e. windward and leeward, and shown in Fig. 4. As a baseline case, for each window orientation, an experiment of the room without a windexchanger was carried out. The room and the windexchanger roofs were flat and the windexchanger was on the roof center; room dimensions, window opening area, windexchanger duct cross section, and wind speed were all kept constant. The windexchanger parameters that varied were the number of openings, the total opening area, the number of subducts, and the wind incidence angle. The window was located at the leeward or at windward facades. The case name for the baseline case is BL and the type of windexchanger and the flow incidence angle form the name of the other cases.

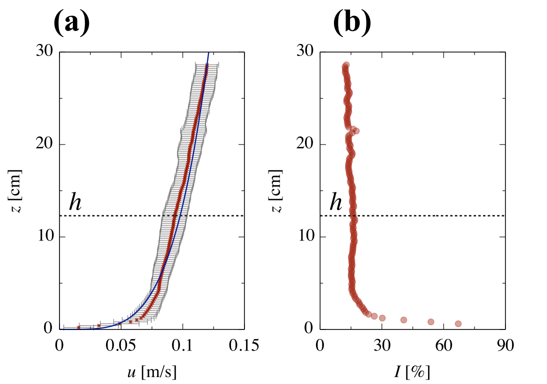

Figure 3: Vertical profiles of the flow in the water channel. (a) Axial component of the velocity, u. The symbols indicate experimental averages with their standard deviation. The solid line is the fit of the experimental data to Eq. (1) (α = 0.251 ± 0.004); (b) The turbulent intensity, I. The dashed line represents the scaled room height h = 12.3 cm.

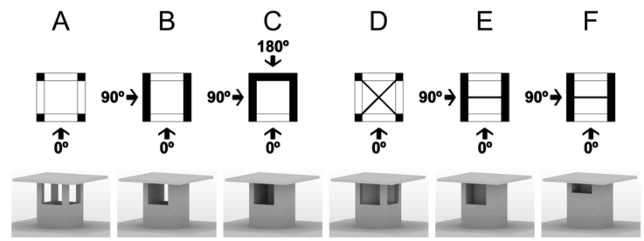

Figure 4: The six windexchangers configurations: (A) with four openings and one duct, (B) with two openings and one duct, (C) with one opening and one duct, (D) with four openings, partitions, and four subducts, (E) with two openings, a partition, and two subducts, and (F) with two openings with half of area, a partition, and two subducts. Top view in the upper part, the arrows indicate the wind incidence angle tested for each one, and isometric view in the lower part.

RESULTS, ANALYSIS AND DISCUSSION

Ventilation flow rate

As measurements have only been performed on the central plane, so as to calculate the room ventilation flow rates through the window and through the windexchanger, it was assumed that the corresponding flow is equal at other planes of the opening. The inlet rate, f_{i-w}, and outlet rate, f_{o-w}, through the window, and the inlet rate, f_{i-WE}, and outlet rate, f_{o-WE}, through the windexchanger were obtained for each case from each velocity vector field in 16 pixels × 16 pixels resolution. The velocity vectors considered to calculate these quantities are pointed out in Fig. 5. For the window, three columns of 26 vectors were considered, the average of the x component of velocity of the three vectors at the same height was obtained and multiplied by the height of the interrogation area (Δz = 0.00204 m) and by the width of the window, i.e. the window out of plane dimension (Δy = 0.052 m). For the windexchanger flows, a similar procedure was performed, in this case a row of twelve vectors were used. The row of vectors was taken one row below the connection of the room with the windexchanger, because at the exact connection there are shadows that reduce resolution. The vertical velocity component was multiplied by the width of the interrogation area (Δx = 0.00204 m) and by the windexchanger out of plane dimension (Δy = 0.025 m). For the window, the positive values were added to account for f_{i-w} and the negative values were added to obtain f_{o-w}. For the windexchanger, the negative values were added to account for f_{i-WE}, and the positive values were added to obtain f_{o-WE}. The reported values of these variables are the average of the 110 velocity fields.

Depending on the ratio of the inlet rate through the windexchanger to the total flow rate through the windexchanger, R, defined by

$$R = \frac{f_{i-WE}}{f_{i-WE} + f_{o-WE}}, \tag{4}$$

the windexchanger is considered as an injector when $R \geq 0.85$, as an extractor when $R \leq 0.15$, and with a mixed behavior when $0.15 < R < 0.85$. For the windward window condition (WW), A0, B0, B90, C90, C180, D0, E90, and F90 are extractors; C0 is the only injector and E0 and F0 have a mixed behavior. For the leeward window condition (LW), C0, E0, D0, and F0 are injectors, C180, B90, and A0 are extractors, and C90, E90, F90, and B0 have a mixed behavior.

The average flow rate, F, is calculated as the average of F_i and F_o. The total inlet rate, F_i, and the total outlet rate, F_o, are calculated as $F_i = f_{i-w} + f_{i-WE}$ and $F_o = f_{o-w} + f_{o-WE}$. Table 1 presents the normalized flow rate, F' and the windexchanger behavior, for each case and for both window conditions. The normalized flow rate, F', is the average flow rate F normalized with the average flow rate of the room with the window at windward and without a windexchanger, i.e. the BL case in the WW condition. As expected, without a windexchanger (BL cases) the ventilation is 30% better when the room has the window at windward than when it is at leeward.

For the WW condition, the cases A0, B90, C0, C90, C180, E90, and F90 have $F' \geq 2.5$. For the LW condition, the cases C0, D0, E0, and F0 have $F' \geq 2.5$. For both window conditions, the maximum value of $F' \approx 4$. For all cases, $F' > 1$ except for BL and B0 in the LW condition.

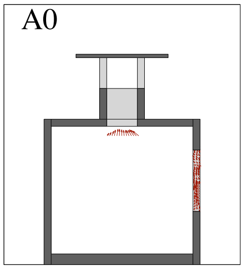

Figure 5: Velocity vectors on the central plane considered to calculate the inlet rate and outlet rate through the window and through the windexchanger, respectively, (red online). Leeward window, A0 case.

Table 1: Normalized flow rate, F', and the windexchanger behavior (injector, I, mixed, M, and extractor E) for each case and for both window conditions; windward, WW, and leeward, LW.

Case	F' [−]		Behavior	
	WW	LW	WW	LW
BL	1	0.7	-	-
A0	3.3	1.3	E	E
B0	1.3	0.8	E	M
B90	4.2	1.9	E	E
C0	2.5	4.9	I	I
C90	2.8	2.3	E	M
C180	3.1	1.7	E	E
D0	2.6	2.7	E	I
E0	1.8	3	M	I
E90	3.1	1.3	E	M
F0	1.7	2.5	M	I
F90	2.7	1.3	E	E

Area percentage with significant flow speed

For this analysis, the average velocity vector field for each case was calculated using the 110 velocity vector fields obtained in 64 pixels × 64 pixels resolution. To calculate the area percentage of the central plane with a significant flow speed, P, only the area inside the room with a height less than 0.072 *m* (1.80 *m* in full scale) was considered. Above this height any improvement in ventilation is not expected to be perceived by the occupants. The value of P was calculated as the percentage of vectors in the evaluated area with a magnitude greater or equal than a reference value, M_r. The reference value of the velocity magnitude $M_r = 0.008$ *m/s* (0.005 *m/s* in full scale) was taken from (Cruz-Salas et al., 2014). Fig. 6 and Fig. 7 show the average velocity vector field on the central plane for the 12 cases per each window orientation WW and LW, respectively. The vectors with magnitude greater or equal than M_r within the evaluated area are pointed out. Table 2 presents the percentage area with a significant speed, P and the windexchanger behavior, for each case and for both window conditions.

For the WW condition, the cases A0, B90, C0, C90, C180, E90, and F90 have $P \geq 38\%$. For the LW condition, the cases C0, D0, E0, and F0 have $P \geq 38\%$. For both window conditions, the maximum value of P is 65% and that for the LW condition is 86%. In a room with a WW ventilation parameters are significantly higher when using windexchangers that behave as extractors; i.e. the cases A0, B90, C90, C180, E90, and F90. In the room with LW, the higher values of the ventilation parameters are obtained using windexchangers with an injection behavior, C0, D0, E0, and F0. In general, the behavior of a windexchanger is not the same for both window conditions, except for A0, B90, and C180, that are the windexchangers without partitions and with an opening at leeward, facing a zone with negative pressure. For the WW condition, as the window has mainly an injection behavior these windexchangers have a mixed behavior, the windexchanger subduct at windward is an injector and the subduct at leeward is an extractor. For the LW condition, the window has an extraction behavior and the windexchanger subduct at windward is an injector with high flow rate and the subduct at leeward has a low flow rate. The effect of the partitions inside the windexchangers duct is negative in all cases when used in a room with a windward window, while for the leeward window condition, its effect is positive when the windexchanger has one opening at windward.

GUIDELINES OF THE WINDEXCHANGER USE

From the previous analysis, it is possible to draw some guidelines for the use of a windexchanger to improve natural ventilation in a room with a windward or leeward window in a hot climate with prevailing winds. These guidelines, summarized in Table 3, are given for different scenarios depending on the prevailing wind type, the window orientation possibility, WOP, i.e. if it is selectable by the designer, or it is restricted at a windward orientation, WW, or at leeward, LW, and the temperature difference between the indoor air and the outdoor air, ΔT. On-an-axis wind type refers to the wind that changes direction during the day on the same axis (like the one characteristic of land and sea breezes and of mountain and valley winds (Givoni, 1981)). In this scenario the window has both orientations, windward or leeward, WW-LW, depending of the direction of the wind. The windexchanger C* refers to the windexchanger C with the opening in the opposite direction to the window opening.

Additionally from the guidelines given in Table 3 for WW and LW conditions, is possible to figure out some others guidelines, that will be verified in future works. For unidirectional and on-an-axis wind type, if the room has the window at a wall parallel to the wind (PW), the window will be close to a zone with negative pressure, thus it is more likely that the window will behavior as extractor. Therefore the windexchangers that behavior as injectors are expected to have better performance than those with an extraction behavior for PW condition. The windexchanger with four openings with partitions, D0, is expected to be suitable for winds in any direction perpendicular to the windexchanger openings. Nevertheless, it is expected that for a wind with variable direction the partitions could have a blockage effect (Blocken et al., 2011), thus the windexchanger with four openings without partitions, A0, could be the best option. An adequate deformation of the roof of A0 can improve its performance (Blocken et al., 2011). The design of this new windexchanger will be subject of a future work. If the ventilation improvement of this windexchanger is significant, it could be recommended for some scenarios of Table 3, especially for scenarios 1 and 3.

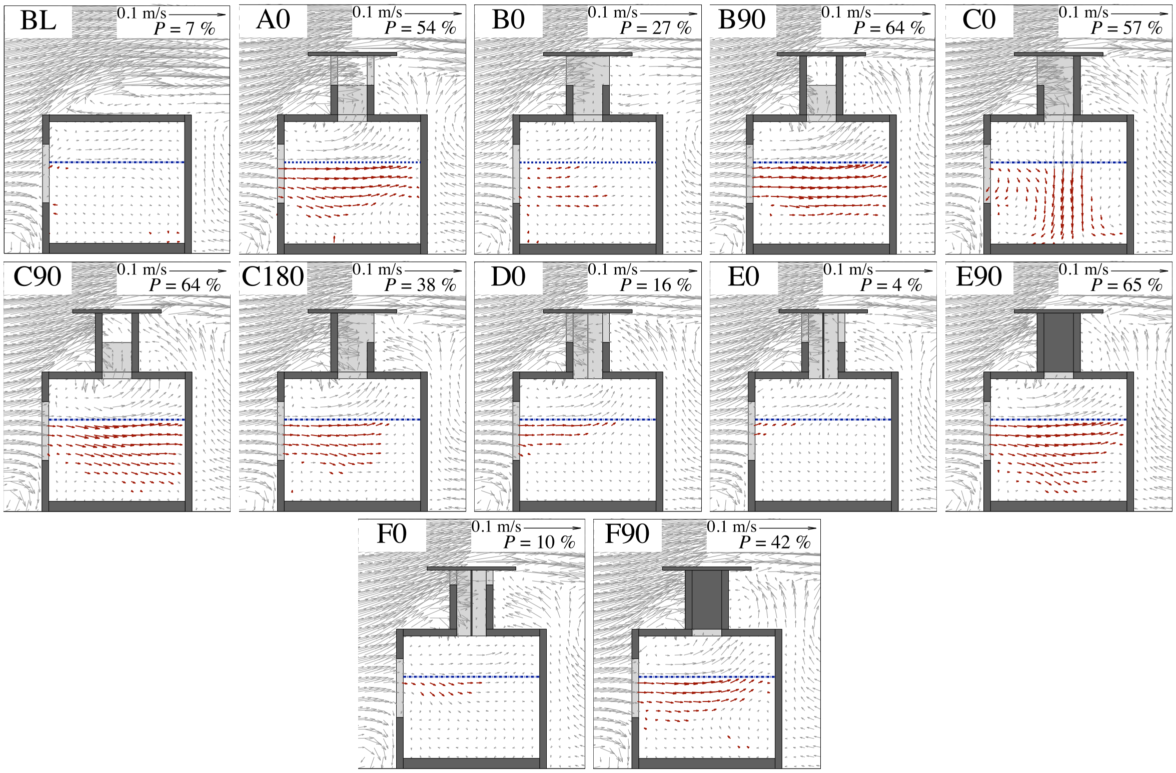

Figure 6: Average velocity vector field on the central plane for the 12 cases of a room with a window at windward. The vectors with magnitude equal or greater than M_r are shown using thicker arrows (red). The horizontal line (blue) is located 0.072 m above the floor (1.80 m in full scale).

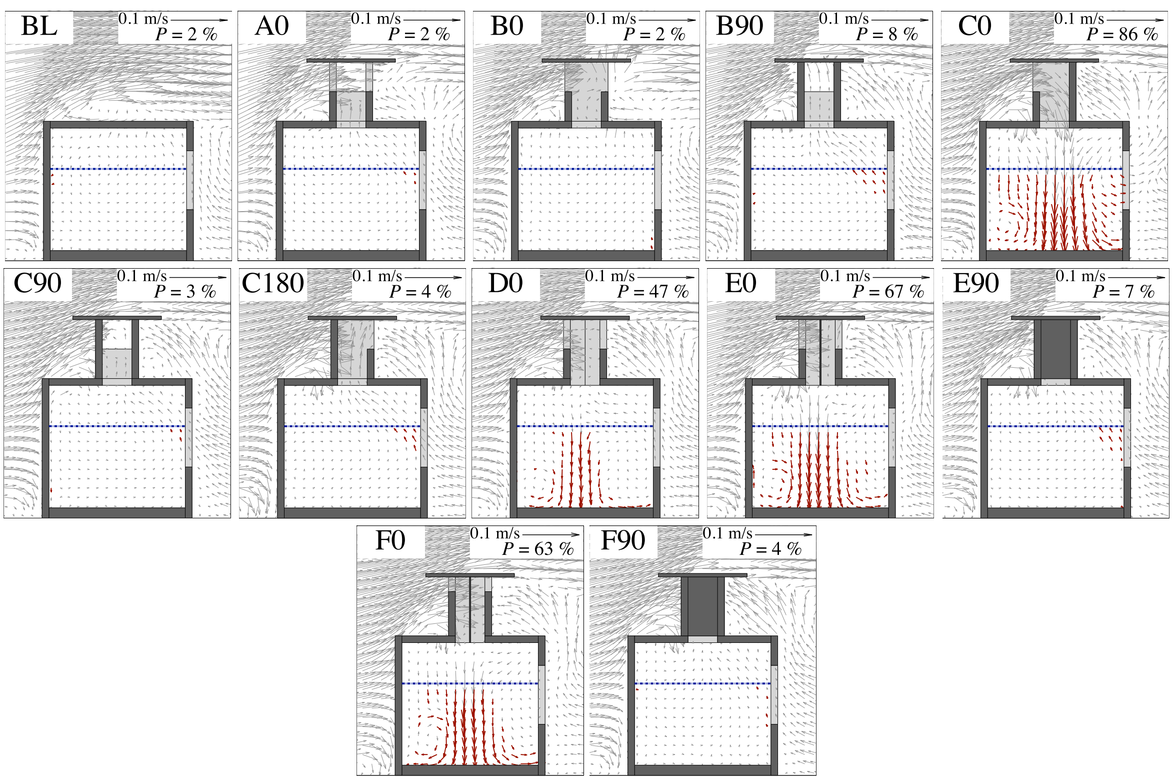

Figure 7: Average velocity vector field on the central plane for the 12 cases of a room with a window at leeward. The vectors with magnitude equal or greater than M_r are shown using thicker arrows (red). The horizontal line (blue) is located 0.072 m above the floor.

Table 2: Percentage area with a significant speed, *P* and the windexchanger behavior (injector, I, mixed, M, and extractor E) for each case and for both window conditions; windward, WW, and leeward, LW.

Case	*P* [%]		Behavior	
	WW	LW	WW	LW
BL	7	1	-	-
A0	54	2	E	E
B0	27	1	E	M
B90	64	8	E	E
C0	57	86	I	I
C90	64	3	E	M
C180	38	4	E	E
D0	16	47	E	I
E0	4	67	M	I
E90	65	7	E	M
F0	10	63	M	I
F90	42	3	E	E

Table 3: Guidelines for the use of a windexchanger for different scenarios depending on the prevailing wind type, the window orientation possibility, *WOP*, i.e. if it is selectable by the designer, or it is restricted at a windward orientation, *WW*, or at leeward, *LW*, and the temperature difference between the indoor air and the outdoor air, ΔT.

Scenario	Wind type	WOP	ΔT	Guidelines
1	Unidirectional	selectable	high	WW and B90
2	Unidirectional	selectable	low	LW and C0
3	Unidirectional	WW	any	B90
4	Unidirectional	LW	high	E0
5	Unidirectional	LW	low	C0
6	On-an-axis	WW-LW	high	B90
7	On-an-axis	WW-LW	low	C*

CONCLUSIONS

This work presents a summary of experimental results of the performance of windexchangers to improve natural ventilation of a single room with a window at windward and at leeward. The room without any windexchanger was used as the baseline case. The parameters used to evaluate the ventilation performance are the area percentage of the central plane with a significant flow speed and the flow rate into the room. These results of both window orientations are compared. From a systematic analysis of these results, guidelines for the use of windexchangers in a room with a window in one of these locations are given. All cases with a windexchanger, except one (B0), show area percentages with a significant flow speed and flow rates higher than that of the case without windexchanger and the window at windward. Nevertheless, the increase in these ventilation parameters ranges from very significant to almost negligible; stressing the importance of the adequate design of the windexchanger. For places with prevailing winds from a fixed direction, in rooms with the window at leeward, the windexchanger should be designed with openings that have an injection behavior. The case with one opening at windward, C0, has the highest area percentage with a significant flow speed, 86%, and produces the highest flow rate, 7.1 times that of the case without windexchanger and the window at windward. The use of a windexchanger to improve natural ventilation in a room constructed or to be constructed in a hot climate with prevailing winds is recommended and it must be selected according to the prevailing wind type, the window orientation possibility, and the temperature difference between the outdoor and the indoor air. Although the guidelines for the use of windexchangers given in this work are set from values of the ventilation performance parameters obtained from only velocity data of the room central plane, these guidelines are expected to be the same of those set from velocity data of the three dimensional space obtained from experiments or simulations.

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