Windexchangers in a building with a window to windward or to leeward: Design guidelines

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ABSTRACT: In this work design guidelines for the use of windexchangers to increase natural ventilation in buildings with a window to windward or leeward are presented. The term windexchanger is used for a small structure, relative to the room size, that is located on the room rooftop and can perform as an intake, as an exhaust, or both, depending on the wind direction and window location. Natural ventilation is a thermal comfort strategy for hot climates that can represent important energy savings. These design guidelines are obtained from the analysis of numerical results of the use of different configurations of windexchangers in a room as a generic building. The numerical simulations were validated with experimental results. As baseline and for comparison, the rooms without windexchanger and with both window orientations were used. The parameter employed to evaluate the ventilation performance for thermal comfort is the volume percentage with significant flow speed within the habitable zone of the room.
Keywords: Natural ventilation; Windexchanger; CFD simulations; Leeward window; Windward window

INTRODUCTION

Natural ventilation is used for maintaining the indoor air quality and for thermal comfort. To evaluate natural ventilation for thermal comfort, the airflow distribution inside the building is necessary. Hence, the generation of knowledge about the airflow distribution in a building is important. Different ventilation passive systems, which promote natural ventilation without the use of external energy, have been studied (Akamine et al., 2008; Khan et al., 2008). The cross-flow ventilation is one of the most used strategies (Karava et al., 2011), because, its implementation by using two openings, one at windward and the other at leeward (Karava et al., 2011), is relatively easy. 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 structure with openings on the rooftop is an alternative. The name employed for this type of structures is not unique in the literature. They are referred as windchatchers (Montazeri, 2011), wind towers (Salfari & Hosseinnia, 2009), monitor roofs (Wang et al. 2010) and windexchangers (Cruz-Salas et al., 2014). The use of terms and classification depends on the author. In the present study the term windexchanger (WE) is used for a small structure, relative to the room size, located on the room rooftop that can perform as an intake, as an exhaust, or both, depending on the wind direction and window location (Cruz-Salas et al., 2014).

The present study has a direct application in low-income houses. In Mexico, those houses represent 58% of a total of 560,368 offered houses in 2014 (SEDATU, 2015). These houses have no air-conditioning installations or a properly design for natural ventilation (Huelsz et al., 2011). Therefore, the improvement of natural ventilation in that type of houses by constructing the WE will increase the hygrothermal comfort of the occupants. In addition, the WE will cost a low percentage of the total cost of the low-income houses. In Fig. 1, the six WE configurations evaluated are taken from the results reported by Cruz-Salas et al. (2014) and Castillo et al. (2015).

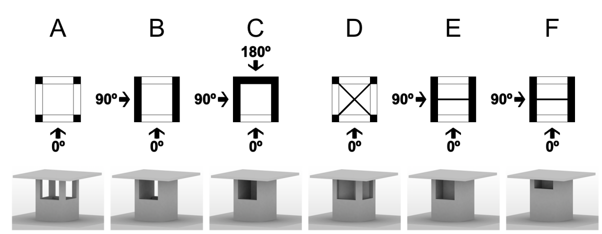


Figure 1: The six windexchangers configurations: (A) with four openings and one duct, (B) with two openings and one duct, (C) with one opening and one duct, (D) with four openings, partitions, and four subducts, (E) with two openings, a partition, and two subducts, and (F) with two openings with half 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.

Guidelines for the use of WEs in a room with a window to both locations (windward and leeward) are set, by using Computational Fluid Dynamics (CFD) simulations. The commercial software COMSOL 5.2 is employed. The simulations are validated with the experimental results reported by Cruz-Salas et al. (2014). The CFD results provide complete information, in the three dimensions, at the interior of the room. This fact is an advantage over the experimental results, which are obtained only from velocity measurements in the central plane of the room. Nevertheless, the experimental results are useful and indispensable for validating the numerical simulations. As in this study the main purpose of increasing ventilation is for thermal comfort, the volume percentage with significant flow speed (VP) is used as the evaluation parameter. The VP is defined as the volume percentage of the room interior volume with a flow speed greater to a reference value. Thus, in the CFD results, the interior volume is discretized and VP is calculated. The VP values are used to compare the air distribution at the interior of the room generated by each combination of window orientation and WE configuration. From this information, the WEs are selected for the possible application scenarios. The generated guidelines summarize the scenarios. These findings are expected to be useful for constructors and designers, in order to enhance natural ventilation in houses already built or to be designed, particularly for low-income houses.

REFERENCE CASE

The reference case has a WE with square-cross-section, one duct, four openings and flat roof (case A, see Fig. 2). It is located at the center of the rooftop of the room. The WE has a height of 1.40 m from the roof, have a square-cross-section of 0.65 m in length and it is designed with a roof eave of 0.64 m, which acts as a solar and rain protection. The reference case also includes a room with interior dimensions W × D × H = 3.0 × 3.0 × 2.7 m^3. The room has a square window at windward, 1.30 m in length, giving a wall porosity (opening area divided by wall area) of 17%, it is centered on the wall and its base is at a height of 0.90 m from the floor.

EXPERIMENTS

The reference case was experimentally studied by using a laboratory scale model 1/25 (Cruz-Salas et al., 2014). In Fig. 2, the model placed in the test section of an open water channel (OWC), where Stereo Particle Image Velocimetry (SPIV) measurements were obtained. The OWC is 6 m long and has a test section of 1.0 × 0.315 × 0.41 m^3. The model is made of transparent acrylic, with the following thickness: 6 mm for walls and room's roof, 9 mm for the floor, and 3 mm for the WE roof. The interior dimensions are W × D × H = 12 × 12 × 10.8 cm^3. The SPIV measurements were performed in the vertical central plane, as shown in Fig. 2b. In the OWC, an atmospheric boundary layer of a suburban area was reproduced. The mean velocity U and turbulence intensity I profiles were measured in the empty test section at the model position but without it, i.e. incident profiles. The obtained friction coefficient of the exponential law is $\alpha = 0.29$ (Bañuelos et al., 2010). The incident profiles are used for the validation study as recommended by Blocken et al. (2008). A reference mean wind speed U_{ref} = 0.089 m/s (0.062 m/s, in full scale) and a reference turbulence intensity of 20% were measured at the reference height z_{ref} taken as the external height of the room h = 12.3 cm (3.075 m, in full scale). The experiments were performed in water applying the dynamic similarity with the Reynolds number $Re = U_{ref}z_{ref}/\nu = 1.23 \times 10^4$, where $\nu = 8.94 \times 10^{-7}$ m^2/s is the kinematic viscosity at the water temperature T_w = 25 ºC.

VALIDATION

This paper presents a CFD study performed with the commercial code COMSOL 5.2 (COMSOL 2013). This section presents the settings for the validation of the reference case. The settings are taken from a previous validation work (Castillo et al., 2014) using the experiments reported by Cruz-Salas et al. (2014).

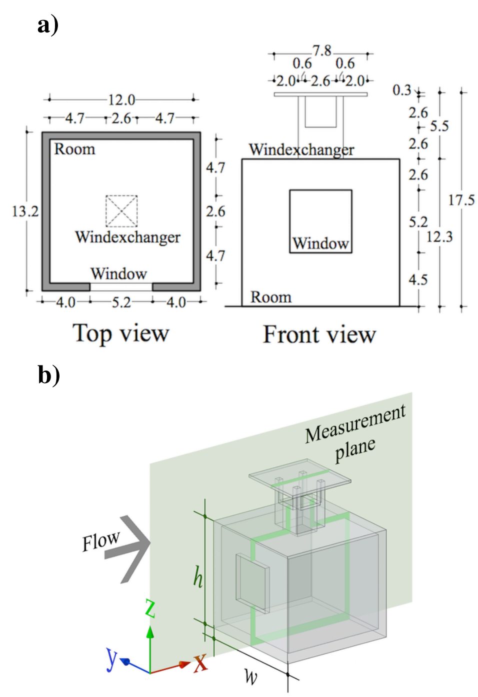


Figure 2: Model of the room with the windexchanger reference case. (a) Top and front view, units in centimetres; (b) Isometric view with the measurement plane and flow direction, where h = 0.123 m and w = 0.132 m are the external height and width of the room model, respectively.

Solvers and convergence criteria

The numerical model of the reference case is solved with the 3D steady RANS equations in combination with the shear-stress transport (SST) k-ω model. The GMRES solver with MULTIGRID-SOR preconditioner is employed for velocity-pressure coupling, and the MULTIGRID-SCGS preconditioner is used for viscous terms of the governing equations (COMSOL 2013). The convergence criterion is obtained when all the scaled residuals are equal or less than10^{-4}.

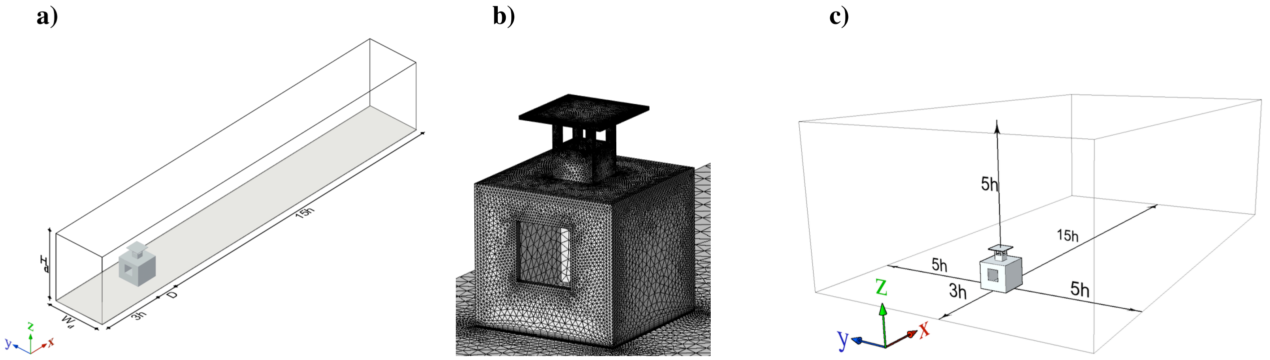


Figure 3: Computational domain with the model of the room with the WE reference case: (a) Perspective view with dimensions of the domain; (b) Isometric view of the room with the WE reference case (grid A with 1,176,225 nodes); (c) Perspective view of the room in its computational domain extended.

Computational domain and grid

The computational domain with the reference case is constructed by following the guidelines by Tominaga et al. (2008), its dimensions are $W_d \times L_d \times H_d = 0.315 \times 2.346 \times 0.41$ m^3 (Figure 3a). A tetrahedral grid is created with 1,176,225 nodes (Figure 3b).

Boundary conditions

The inlet boundary conditions are set according to the experimental velocity and turbulent profiles. The velocity profile is defined by the logarithmic law, $U(z)=(u^*_{ABL}/\varkappa)ln((z+z_0)/z_0)$, with the atmospheric boundary layer (ABL) friction velocity, u^*_{ABL}=0.007m/s, the von Karman constant, $\varkappa$ = 0.42, the roughness length, z_0 = 0.0005 m, and the height coordinate, z. The turbulent kinetic energy profile, $k(z)=(\sigma_u^2(z)+\sigma_v^2(z)+\sigma_w^2(z))/2$, is calculated from the standard deviation of each velocity component for x-direction, σ_u, for y-direction, σ_v, and for z-direction, σ_w. The turbulence dissipation rate and specific dissipation rate profiles are obtained, $\varepsilon(z) = u^{*3}_{ABL}/\varkappa(z+_{z0})$ and $\omega(z)=\varepsilon(z)/C_\mu k(z)$, respectively, with ABL the empirical constant C_μ = 0.09 (Tominaga et al. 2008). The standard wall functions (COMSOL 2013) are set at ground surface and at lateral walls. The zero static pressure is applied on the rear face of the domain. The free slip condition at the top boundary is used to simulate the air-water interface. In Fig. 4, the velocity profile and turbulent profiles, $k(z)$ and $\omega(z)$ at the inlet and incident building position in the empty domain are presented, showing that their streamwise gradients are negligible.

Validation

In Fig. 5, the experimental and CFD velocity vector fields at the central plane are shown, as well as the streamwise speed ratio, u/U_{ref}, along a horizontal line, L_h. The CFD simulations results show good agreement whit the SPIV experimental results. The averaged difference of streamwise speed ratios is lower than 20%.

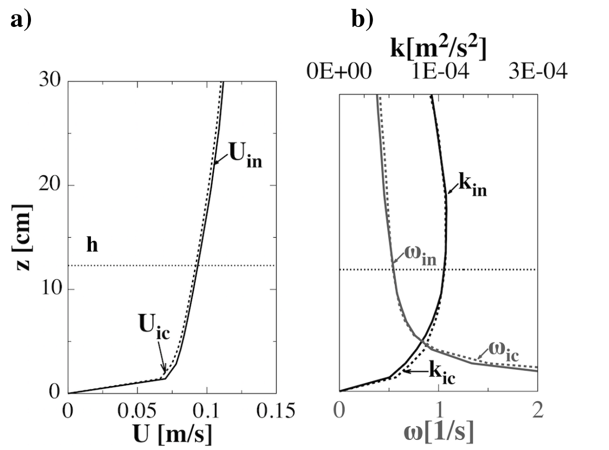


Figure 4: Vertical profiles of (left) the mean velocity, U; (right) the turbulent kinetic energy (dark line), k, and the specific dissipation rate (gray line), ω, at the inlet (continuous line) and at the incident building position (dashed line) in the empty domain. The subscripts in and ic refer to inlet and incident, respectively. The height of the model (h) is 0.123 m.

WINDEXCHANGERS EVALUATION

To evaluate the air distribution in an isolated generic room with different WEs and window locations, the numerical model, presented in the previous section, is employed. Note that, the numerical model simulates the experimental conditions: the distance of the lateral walls and the air-water interface. Those conditions can influence the dynamic of the ventilation in the room. To reduce these effects and to obtain a more reliable result a new domain is created by following the guidelines by Franke et al. (2007), where the lateral and the top distances from the exterior surface of the room to the lateral and top boundaries, respectively, are five times of the characteristic length (5 × h), see Figure 3c. For these extended boundaries the symmetry boundary condition is applied. Additionally, the domain is rescaled to full scale and air used as working fluid. In that respect, the inlet vertical profiles of $U(z)$, $k(z)$, $\varepsilon(z)$ and $\omega(z)$ are calculated by applying the dynamic similarity with Re.

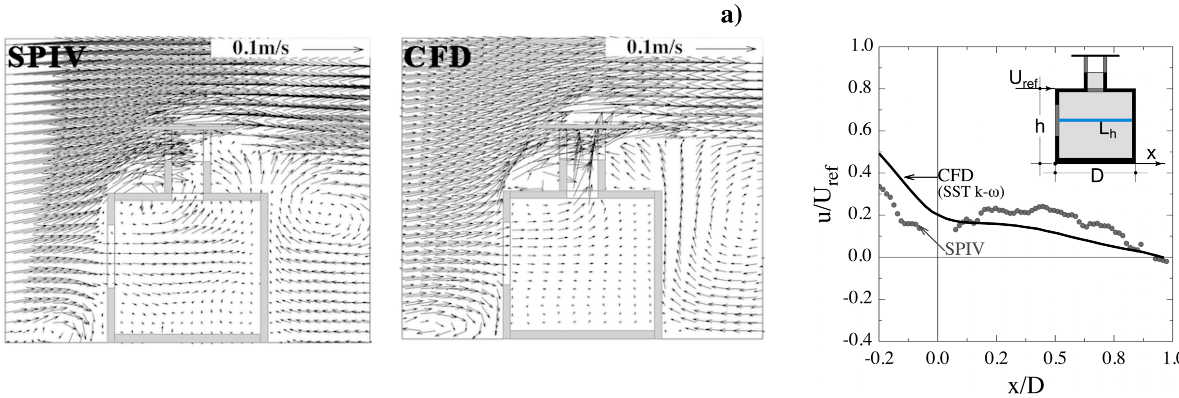
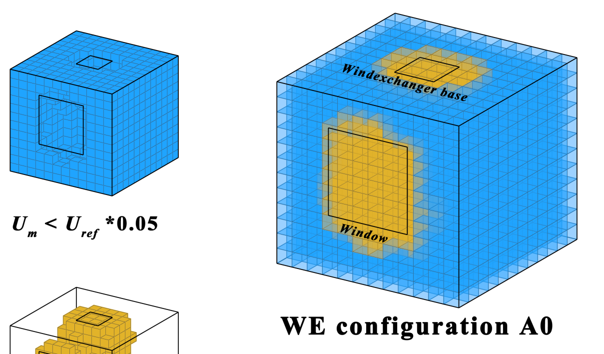


Figure 5: Experimental (SPIV) and numerical (CFD) results: (a) Velocity vector field at the central plane and (b) Streamwise speed ratio u/U_{ref} along the central line L_h.

The values for the full scale are U_{ref} = 1.0 m/s, z_{ref} = h = 3.075 m, and α = 0.25. The six WE configurations evaluated in the next section are shown in Fig. 1.

Volume percentage with significant flow speed

To calculate the volume percentage with significant flow speed, *VP*, the interior volume is discretized in 1,728 cells of which the velocity magnitude, *i.e.* the flow speed, U_m, is obtained. The *VP* is the sum of cells which their value U_m is greater or equal than U_{ref} * 0.05. Figure 6 shows an example of this analysis applied to the WE configuration A0 with a window at windward. Table 1 presents the value of *VP* for all the WE configurations with both window locations. These results show that the best WE for a window at windward is D0 with *VP*=70%, and for the window at leeward, the best WE is C0 with *VP*=41%.



Velocity magnitude	Cells	Percentage
$U_m < U_{ref}$ * 0.05	1336	77
$U_m \geq U_{ref}$ * 0.05	392	23
Total	1728	100

Figure 6: An example of the volume percentage with significant flow speed analysis. Case A0 with a window at windward.

Table 1: Volume percentage with significant flow speed, VP, per each WE configuration.

WE Configurations	*VP* *WW*	*VP* *LW*
A0	23	16
B0	52	14
B90	22	15
C0	9	41
C90	17	12
C180	43	8
D0	70	36
E0	33	20
E90	24	20

Table 2: 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.

Scenario	Wind type	WOP	Guideline
1	unidirectional	selectable	WW and D0 or LW and C0
2	unidirectional	WW	B0 or D0
3	unidirectional	LW	C0 or D0
4	on-an-axis	WW-LW	D0 or E0

DESIGN GUIDELINES

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 2, 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. For these guidelines the temperature difference between the indoor air and the outdoor air is considered as negligible. 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 on the hour of the day. Additionally from the guidelines given in Table 2 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. 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 2, especially for scenarios 1 and 3.

CONCLUSION

The goal of this work is to provide design guidelines of the use of square-cross-section windexchangers, WE, for thermal comfort in hot climates. To obtain these guidelines, CFD simulations are performed with the 11 configurations of WE, the WE centered on the rooftop of an isolated generic room. The volume percentage with significant flow speed within the room is used as evaluation parameter. A reference case, the WE with one duct, four openings, and a window at windward, and the incidence wind normal to one of the WE openings is used to validate the simulations with experimental results. Four scenarios are generated for two different window locations (windward and leeward) and two wind behaviors (prevailing or on-an-axis).

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