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Evaluation of the airflow distribution in naturally ventilated buildings using CFD

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ABSTRACT: In Mexico, 22.2% of the total greenhouse gas emissions corresponds to the building sector. In buildings located in warm climates, the use of bioclimatic design strategies as natural ventilation can contribute to the mitigation of these emissions. In this work, the evaluation of natural ventilation using parameters that consider the indoor airflow distribution is presented. The design of a new high educational building that will be built in a warm climate is used as an application example. The airflow distribution is solved using a Computational Fluid Dynamic (CFD) simulation in real scale. The CFD simulation is validated using experimental results of a simplified building geometry taken from the literature. The natural ventilation evaluation is done in one representative space of the building, considering other spaces closed. The normalized velocity magnitude and the homogeneity index are evaluated in two planes of interest giving values up to 0.34 and 62%. The age of air associated parameters consider the whole space volume, air renovations per hour are 36.6h^{-1} and ventilation efficiency is 40%. The ventilation of the space overpasses the air changes per hour required by the air quality Mexican standard.

KEYWORDS: Natural ventilation, Airflow distribution parameter, CFD, Positive feedback, Air renovation per hour.

1. INTRODUCTION

In Mexico in 2017, the energy consumption of the residential, commercial and public buildings was 1103.6 PJ, representing 20.6% of the total national consumption [1,2]. The associated greenhouse gas emissions are estimated in 98.1 MT-CO2eqv corresponding to 22.2% of total emissions in the country [3]. Planning Post-Carbon Cities in countries like Mexico represents a paradigm change in energy production and consumption. New buildings in Mexican cities must be designed as net zero energy buildings or at least with a low energy consumption [4].

More than 2/3 of the Mexican territory has warm climate [5], where several cities are located, increasing the use of mechanical cooling and ventilation systems to provide thermal comfort to the occupants.

Natural ventilation is a bioclimatic design strategy that can reduce the energy consumption of buildings in warm climates [6,7]. This strategy uses wind and thermal buoyancy to introduce outdoor air into the buildings, with the aim to increase airflow speed, especially in the living zone. The evaporation of skin sweat enhanced by the airflow speed around the human body decreases its temperature and increases the occupant's thermal comfort. This is an evaporative cooling by phase change of the sweat.

If the outdoor air quality is good enough, natural ventilation can provide adequate air quality in the indoor. Currently, in many big cities, the outdoor air quality is poor, generally due to the emitted gases of the fossil fuel combustion by the transport system [8]. The use of natural ventilation in the planning of the Post-Carbon Cities could contribute to a positive feedback case, which can be figured as follows. In Post-Carbon Cities, the use of electric or hybrid cars must be included, allowing the reduction of greenhouse gases and other pollutants within the cities. Also, the implementation of renewable energies as the principal energy source in the cities would reduce the gas emissions to the atmosphere. These facts will improve the air quality of the cities and increment the use of natural ventilation, which in turn will decrement the energy consumption and will reduce the greenhouse gas emissions to the atmosphere.

In recent years, the use of computational fluid dynamic (CFD) numerical simulations for the design and evaluation of naturally ventilated buildings has increased. CFD studies are divided in no-coupled and coupled. The no-coupled studies separately consider the outdoor and the indoor of the building, using CFD to simulate airflow in at least one of these spaces [9,10]. The coupled studies simultaneously solve the airflow in the outdoor and the indoor of the building, this is the best approach to the real phenomena [6,11]. Nevertheless, coupled studies require more computational capacities than no-coupled ones.

For naturally ventilated buildings, the evaluation of the airflow distribution at the indoor allows to quantify the air quality and the occupant's thermal comfort. However, the most common parameters used in the literature to evaluate ventilation: the air exchange rate I (1/s), the air changes per hour ACH (1/h) and the volumetric flow rate Q (m^3/s), do not evaluate the airflow distribution [12]. In this paper, evaluation parameters that consider the airflow distribution are used. The evaluation is developed using a CFD coupled simulation of a new high educational building that will be located in a warm climate. This paper presents the study case (application example) in section 2, the description of the evaluation parameters in section 3, the CFD validation in section 4, the evaluation of the indoor airflow distribution in section 5 and the conclusions of the paper in section 6.

2. STUDY CASE (APPLICATION EXAMPLE)

The design of a new high-educational building that will be built in the Instituto de Energías Renovables of the Universidad Nacional Autónoma de México (IER-UNAM, acronym in Spanish) is considered as the application example. The Institute is located at Temixco, Morelos, Mexico, which has warm climate. The maximum temperatures, around 35 °C, are in the spring (April and May), in the hot and dry season. In the summer, the rains reduce the temperature and increase humidity. Thus, the bioclimatic design strategies for this new building are focused on increase the airflow speed in the living zone to enhance the skin sweat evaporative cooling of the occupants. The new building is designed with natural cross-ventilation as one of the main bioclimatic strategies to promote thermal comfort conditions. When this strategy will be not enough, it will be complemented with an evaporative cooling system to reduce the temperature of the air that enters the building using sprinklers. When the wind speed is not enough, electric extractors will be used. The new building will have three levels of classrooms, laboratories, offices and a cafeteria. The building is planned with a height of 12.0 m and a rectangular base of 57.7 m × 15.3 m. The largest facades have been designed to have a north and south orientation. During the daylight, the prevailing wind comes from south. The ventilation evaluation presented in this work is done in a classroom of the second level that is designed to be naturally ventilated by cross-ventilation. The coupled CFD simulation reproduces the building design as an isolated building (without neighbors) in a flat terrain. It is considered that all spaces are closed, excepting the classroom under analysis. Fig. 1 shows a perspective front view of the new building in the computational domain.

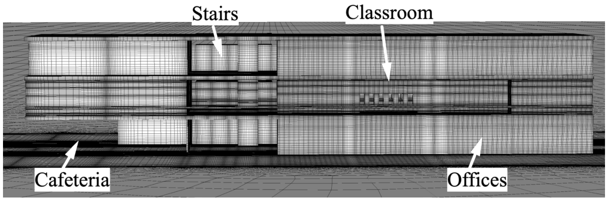

Figure 1. Front view of the south facade of the building that will be built at IER-UNAM.

3. EVALUATION PARAMETERS

The most used evaluation parameters in natural ventilation research are the air exchange rate $I = Q/V$ (1/s), where Q (m^3/s) is the volumetric flow rate at inlets and V (m^3) is the total indoor air volume, and the air changes per hour $ACH = 3600I$ (1/h). By definition, these two parameters do not consider the indoor airflow distribution. The ventilation is considered as an ideal piston flow and their results overestimate the natural ventilation [12]. In this work, the use of evaluation parameters that consider the indoor airflow distribution using CFD simulations is analyzed. The parameters related with the indoor velocity distribution are the normalized velocity magnitude U/U_{ref} (-) plotted in contour plots and vector fields for qualitative evaluation, and the average of the normalized velocity magnitude $\overline{U}/U_{ref}$ (-) and the homogeneity index H (-) for quantitative evaluation. H is the measure of the velocity homogeneity of the airflow in a plane or a volume and it is defined as

$$H = 1 - \frac{\sigma_U}{\overline{U}} \qquad (1)$$

where σ_U (m/s) is the standard deviation of the magnitude velocity and $\overline{U}$ (m/s) is the average of the magnitude velocity [13]. Additionally, the use of the age of air associated parameters is proposed. The age of air concept is defined as the time that an air parcel has stayed inside the building since it has entered through one of the building openings [12]. Internal age τ_i (s) is the age at every point in the indoor air volume V. Given that flows of natural ventilation are turbulent, τ_i is a function of time and has not a determined value, thus it is represented by a probability distribution function at points of V. The age of air associated parameters are estimated from local averages, *i.e.* at each point, and spatial averages, *i.e.* over V. Local mean age of air $\overline{\tau_i}$ (s) is the estimation of the internal age in every point in V. Using an iterative methodology, it is obtained the spatial distribution of $\overline{\tau_i}$ [14]. As qualitative evaluation, contour plots of $\overline{\tau_i}$ are presented. The estimation of the air renovation time, named in the literature as the spatial average of residence time $\langle \tau_r \rangle$ (s), is given by

$$\langle \tau_r \rangle = 2\langle \tau_i \rangle \qquad (2)$$

where $\langle \tau_i \rangle$ (s) is the spatial average of internal age in V. The renovation time can be expressed by air renovations per hour ARH (1/h) defined as

$$ARH = \frac{3600}{\langle \tau_r \rangle} \qquad (3)$$

The ventilation efficiency ϵ (-) is defined as the ratio between the air renovation time of the most efficiency ventilation system, *i.e.* the ideal piston flow, and the air renovation time of the case in evaluation,

$$\epsilon = \frac{\tau_n}{2\langle\tau_i\rangle} \qquad (4)$$

where $\tau_n = V/Q$ is the nominal time. The values of $\langle\tau_r\rangle$, ARH and ϵ are also used in the quantitative evaluation.

4. CFD VALIDATION

The CFD simulations are performed using the commercial software ANSYS-Fluent 19.0 [15].

For the validation of the CFD simulations, experimental results reported in the literature [16] of a closed rectangular building are used. The experiment is performed in a wind tunnel at the Meteorological Institute of the University of Hamburg with a scale model (1/200) of the building. The model represents a rectangular structure of $1.2 y_{ref} \times 0.8 \ y_{ref} \times y_{ref}$ (width × length × height), where $y_{ref} = 0.125$ m is the model height. The reference velocity $U_{ref} = 4.51$ m/s is the velocity of the airflow not disturbed by the model at y_{ref}. The building Reynolds number is $Re_b = \frac{U_{ref} y_{ref}}{\nu} = 3.6 \times 10^4$, where ν m^2/s is the kinematic viscosity. The Laser Doppler Velocimetry (LDV) technique is implemented at the vertical central plane and at the horizontal plane at $0.28 y_{ref}$, obtaining two components of the velocity vector fields [16]. Fig. 2 shows the isometric view of the model with the vertical central plane and the horizontal plane at $0.28 \ y_{ref}$ where the velocity components are measured. Three lines of interest are used, one vertical above to the model roof and two horizontals in front to the model that are at different height and position respect to the vertical central plane.

The model dimensions and geometry, as well as the experimental conditions [16] are reproduced in the CFD simulations. The computational domain generation and the general solver settings are taken from the best practice guidelines of CFD simulations of natural ventilation [17-19]. The SIMPLEC scheme algorithm is used for the pressure-velocity coupling. Second order discretization is used for the convective and viscous terms and for the turbulence model equations. The number of iterations is 10,000 and the scaled residuals for all parameters are less than 10^{-6}. The CFD validation consists of two sensitive analyses: the impact of the grid resolution and the impact of the turbulence model selection. These sensitive analyses are done for the three lines of interest, normalizing the velocity components with respect to U_{ref} : *u*-component and *v*-component for the vertical line and *u*-component for the horizontal lines.

For the sensitive analysis of the impact of grid resolution, four grids are built using the refining factor $\sqrt[3]{2}$ to obtain two fine grids and the coarsering factor $1/\sqrt[3]{2}$ to obtain one course grid. The factors are applied on each coordinate direction to a reference grid. The reference grid has 196,614 cells. These CFD simulations are performed using the RNG k-ε turbulence model. The course grid and the two fine grids present an average difference respect to the reference grid of the normalized velocity up to 5% along all the interest lines. The difference decreases when the number of cells increases. Other works of natural ventilation accept results with a difference below 10% [6,11,17-19]. Thus, it is concluded that the reference grid provides an enough accurate solution in a short computational time.

For the sensitive analysis of the impact of turbulence model selection, three of the most used turbulence models in natural ventilation studies (RNG k-ε, R k-ε and SST k-ω) are tested using the reference grid. The results obtained with these turbulence models are compared with the experimental results of [16]. Along the vertical line (vl_vp), that is above the model (Fig. 2), the three turbulence models present a difference up to 14%, while in the horizontal line (hl_hp), in front the model, the differences are up to 11% and in the horizontal line (hl_vp) are up to 6%. Fig. 3 shows the normalized velocity *u*-component of the

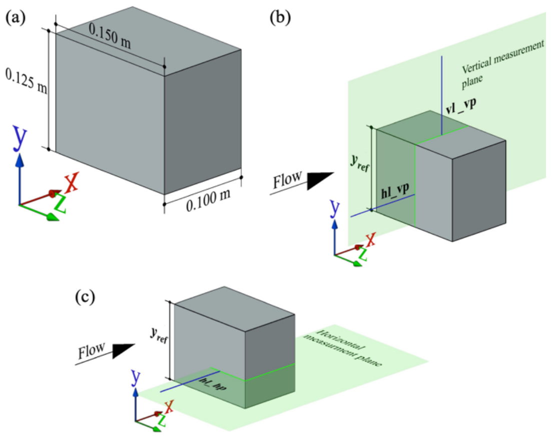

Figure 2. Isometric view of the closed rectangular building (scaled model), planes of measurement and lines of interest: (a) dimensions of the building; (b) vertical central plane; (c) horizontal plane at 0.28$_{yref}$.

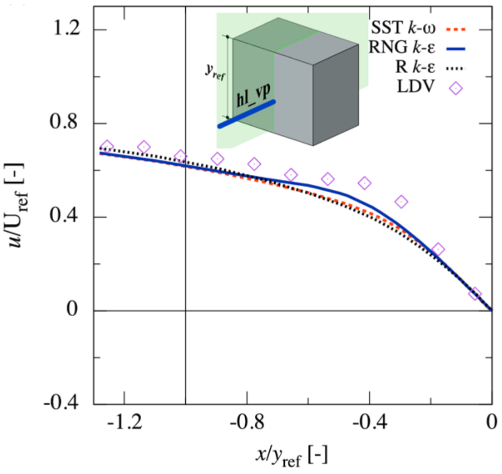

Figure 3. Normalized velocity u-component from experiments and simulations. U_{ref} = 4.51 m/s is the reference velocity taken at the height of the building y_{ref}=0.125 m.

experimental and simulation results for hl_vp. Fig. 4 shows the velocity vector fields at the vertical central plane from the experiment and from the simulation. The airflow structure and size of the vortex formed between the ground and the windward building facade are reproduced by the CFD simulation. The reproduction of the flow structure and of the vortex is important, because they generate the cross-ventilation, which is the natural ventilation strategy evaluated in this work.

At the interior of buildings, the RNG k-ε and SST k-ω turbulence models are extendedly used to obtain the indoor airflow distribution [6,11,19]. In a previous work [20], the validation of the simulation of the indoor airflow distribution was reported. This validation follows the same methodology described above for the outdoor airflow. An isolated building is reproduced in a coupled computational domain. The building is a single room with two axial windows, each of them in the windward facade and the leeward facade, respectively. The RNG k-ε turbulence model shows the minimum average difference of normalized *u*-velocity, with respect to the experimental results, taken in an interest horizontal line across the center of the windows. The qualitative comparison of the velocity vector fields is shown in Fig. 5. It is observed that the structure and size of the exterior sill vortex and the interior vortexes are reproduced [20]. Thus, it is concluded that the RNG k-ε turbulence model with the reference grid provide an accurate solution. Thus, the CFD simulation can be considered validated.

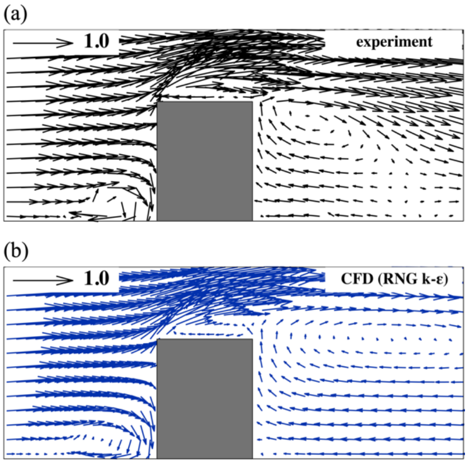

Figure 4. Velocity vector fields in the vertical central plane of the closed rectangular building: (a) experimental results of [16]; (b) CFD simulation results using the RNG k-ε turbulence model.

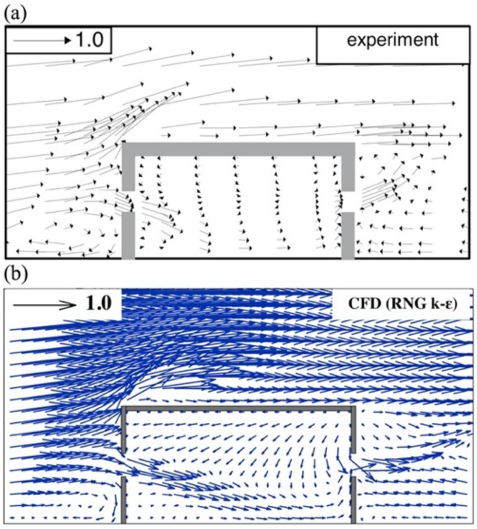

Figure 5. Velocity vector field in the vertical central plane of the building with cross-ventilation: (a) CFD simulation results using the RNG k-ε turbulence model. Taken from [20].

5. EVALUATION OF THE AIRFLOW DISTRIBUTION

The validated CFD simulation is taken as base to generate the domain with the new building in real scale. The new building is considered as isolated in a flat terrain. The grid of the domain with the new building has 19,472,823 cells. Fig. 6 shows views of the building grid where all spaces are closed with the exception of the classroom under analysis. In the classroom, the windows in both facades are open. One bottom vent and one top vent are open in the South facade and in the North facade, respectively. The prevailing wind in occupancy hours comes from the South to the North. The windward windows and the vent in the South facade are observed in the corridor closed-up. The general solver settings are conserved, with the exception of the iterations number, that are increased to 50,000, and the scaled residuals for all parameters, that are less than 10^{-4}. The incident velocity profile to the building is the characteristic of a sub-urban terrain and reproduces the atmospheric boundary layer for a sub-urban region, using the average of the maximum velocity at the IER-UNAM [21]. $U_{ref} = 3.0$ m/s is taken at $y_{ref} = 12.0$ m (building

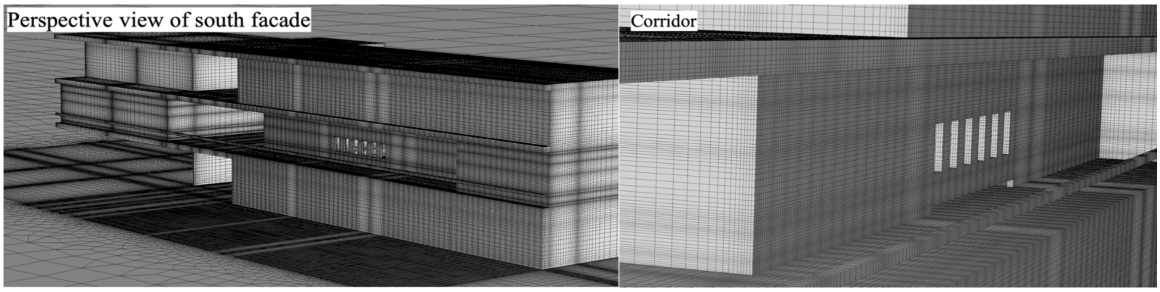

Figure 6. Perspective view of south facade of the building and corridor close-up view (grid with 19,472,823 cells).

height), giving $Re_b = 2.3 \times 10^6$. The turbulent parameter profiles are estimated following the recommendations of the best practice guidelines [17-19].

$\overline{U}/U_{ref}$ and H are evaluated in the zone in the classroom from 0.50 m to 1.80 m above the floor, where the air velocity has a greater impact on the occupants' comfort, this zone is named the interest zone. The calculated age of air associated parameters consider the total indoor air volume $V = 259.2$ m^3. Two planes are selected for the evaluation of the natural ventilation. The vertical plane is taken at the mid width of the window nearest to the classroom center, being the fourth window. The horizontal plane is taken at the mid height of the windows ($y = 1.45$ m).

Results of $\overline{U}/U_{ref}$ and $\overline{\tau_i}$ on the vertical plane are shown in Fig. 6. In the interest zone of this plane $\overline{U}/U_{ref} = 0.34 \pm 0.13$ and $H = 0.62$. The velocity vector field shows a jet from the windward to the leeward windows and a vortex above the jet with an outflow in the top vent of the leeward facade. The interest zone presents the smallest values of $\overline{\tau_i}$, being less than 48 s (0.8 min), while in the vortex above the jet, $\overline{\tau_i}$ are larger than 72 s (1.2 min).

Fig. 7 shows the results of $\overline{U}/U_{ref}$ and $\overline{\tau_i}$ on the horizontal plane. In the interest zone of this plane $\overline{U}/U_{ref} = 0.28 \pm 0.14$ and $H = 0.51$. The velocity vector field shows incoming jets forming a main flow from the windward to the leeward windows. One vortex is formed at the right side of the classroom. The incoming jets present the smallest values of $\overline{\tau_i}$, being less than 24 s (0.4 min). In the area close to the leeward facade, the values of $\overline{\tau_i}$ are between 24 s (0.4 min) and 48 s (0.8 min). The vortex located along the right side of the classroom and the stagnation zone located at the left bottom corner formed by the left wall and the windward facade present the larger values of $\overline{\tau_i}$, being larger than 48 s (0.8 min).

The calculated age of air associated parameters are: spatial average of internal age $\langle \tau_i \rangle = 49.2$ s, air renovation time $\langle \tau_r \rangle = 98.4 s = 1.6$ min, air renovations per hour $ARH = 36.6$ h^{-1} and ventilation efficiency $\epsilon = 0.40$.

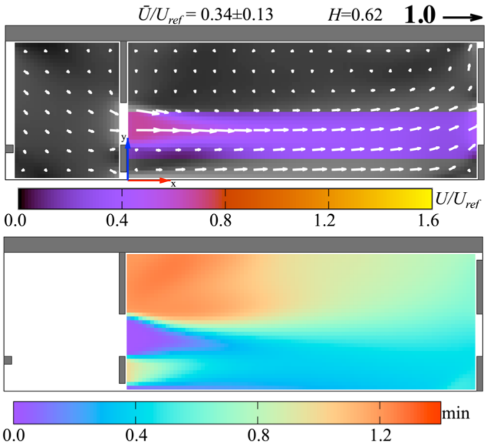

Figure 7. Normalized velocity vector field with the normalized velocity magnitude U/U_{ref} contour plot in the interest zone and counter plot of local mean age of air $\overline{\tau_i}$ at the vertical plane.

On other hand, the parameters that do not consider the airflow distribution are: volumetric flow rate $Q = 6.6$ m^3/s, air exchange rate $I = 0.025$ s^{-1} and air changes per hour $ACH = 91.5$ h^{-1}. The Mexican standard for air quality [22], for educational buildings specifies the minimum of $ACH = 6.0$ h^{-1}. Thus, ACH largely overpasses the minimum, when maximum wind speed is considered. By definition, ACH considers the ventilation provided by a piston flow, which is an ideal ventilation case, overestimating the real air renovation. It is important to point out that even ARH is larger than the minimum ACH recommended by the Mexican standard, by more than six times.

6. CONCLUSIONS

Parameters to evaluate airflow distribution for natural ventilation studies are presented and applied to an example. Average of normalized velocities and the homogeneity index from the velocity distribution and the age of air associated parameters are proposed as quantitative evaluation parameters. The application example is a classroom in a new high educational building that will be built in a warm climate. The evaluation is performed using CFD numerical simulations, where in the same computational domain the outdoor and the indoor of the building are considered (coupled approach).

In the interest zone, the averages of normalized velocity magnitude are 0.34 ± 0.13 and 0.28 ± 0.14 for the vertical and the horizontal planes, respectively. The homogeneity index is 0.62 and 0.51 for the vertical and the horizontal planes, respectively. The age of air associated parameters consider the whole indoor air volume. The air renovation per hour and the ventilation efficiency are 36.6 h^{-1} and 0.40, respectively. Therefore, the parameters that take into account airflow distribution indicate a satisfactory natural ventilation in the classroom.

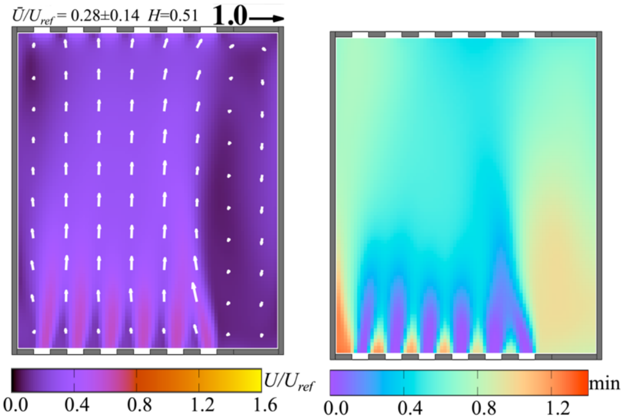

Figure 8. Normalized velocity vector field with the normalized velocity magnitude U/U_{ref} contour plot in the interest zone and counter plot of local mean age of air $\overline{\tau_i}$ at the horizontal plane.

The result of the air changes per hour 95.1 h^{-1}, a parameter that does not consider the airflow distribution, also indicate a satisfactory natural ventilation in the classroom, overpassing for more than fifteen times the minimum specified by the Mexican standard.

The natural ventilation parameters that take into account the airflow distribution, excepting the ventilation efficiency, can be used to evaluate the ventilation in a specific interest zone and can help in the design of new buildings or improvement of existing building in terms to provide occupants' thermal comfort and good air quality at the interior. Also, it is recommended to use the parameter air renovations per hour that gives a more realistic evaluation of the air renovation in buildings than the parameter air changes per hour.

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