A combined CFD-Network method for the cross-ventilation assessment in buildings

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1 INTRODUCTION

1.1 *Background*

It is well known that the natural ventilation of a building is driven by the combined forces of wind and thermal buoyancy. However, when opening areas are large enough, and except for high volumes, the natural ventilation is mainly driven by the wind forces. So, for the natural ventilation assessment in tropical warm climates, the coupling between the thermal forces and the wind driven forces is generally assumed as negligible.

The assessment of the cross-ventilation efficiency is evaluated by considering the wind speed levels inside the buildings, the flow-rates through the openings or more globally the air change rate (ACH). All these characteristics are fundamentally depending on the external wind pressure at the openings. When buildings have no-standard shapes or when the flow is perturbed by close obstacles, these external wind pressures have to be evaluated either from wind tunnel tests or computational fluid dynamics (CFD) methods. Typically CFD computation domains cover an area of almost 500 m x 500 m, allowing taking into account the effects of neighbouring buildings. The mesh should be refined enough at the obstacles and if needed the flow inside the building could be computed simultaneously, but with a high cost in terms of computation times and power. In that context, macroscopic approach can be used to qualify the air change rate and the indoor air behaviours.

For a simple volume with two openings, Aynsley et al. (1977) wrote a formulation of the cross wind flow rate as a function of the openings area, their aerodynamic discharge coefficients, and the reference wind velocity upstream the building :

$$Q = \sqrt{\frac{Cp_1 - Cp_2}{\frac{1}{A_1^2 C_1^2} + \frac{1}{A_2^2 C_2^2}}}\, U_{WIND} \qquad (1)$$

Where A_1 and A_2 are the area of the openings 1 and 2, C_1 and C_2 their discharge coefficients given as functions of the openings aerodynamic behaviors, Cp_1 and Cp_2 the pressure coefficients on the outside walls and U_{WIND} the reference wind velocity.

This method is useful for a single ventilated volume with two openings, but if the number of openings is greater or if the internal volume is divided in sub volumes, a resolution for non linear system has to be used especially when the rooms arrangement give a network with more than one nodes.

The simplified macroscopic approach considers the pressure constant inside each volume and the indoor velocity negligible compared to the flow velocity inside the openings. The first hypothesis is valid up to envelope porosities of about 10%-30%, depending on the internal fittings and the opening locations (Serfert *et al.* ,2006 ; Karava *et al.* ,2007).

The thermal comfort inside buildings naturally ventilated in tropical warm climate depends among others on the indoor air temperature and on the indoor velocity magnitude. These parameters depend on the air change rate (ACH), on the openings characteristics, on the envelope thermal behaviour and the indoor fittings.

The thermal comfort can be quantified by using the adapted PMV index suggested by Fanger (2002) that predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Wang et al. (2003) suggested a new formula depending on both internal temperature and velocity for humid and warm climate where occupants can support higher temperature than in temperate climates. So designers have to define the indoor velocity but by avoiding as much as possible the full computation of the indoor flow in order to reduce computation time. The quickest way could be to use analytic functions between indoor velocity and inlet velocity. Profiles of the velocity on a center line between openings are given for simple geometries by Karava *et al*. (2010).

1.2 *Purposes*

In this paper we present the development of a combined CFD-Network software ("UrbaWind – Natural Ventilation") which performs the calculation of the outdoor wind combined with a macroscopic method for the evaluation of the mass flow rates through the openings. Air exchange rates are function of the external wind conditions taking into account the regional wind climatology. Futher data about thermal comfort can be delivered as global indoor velocity and Personal Mean Vote index

The mass flow rates across air inlets and openings, as well as the pressure fields on the building envelope are computed for every wind incidence, considering a wind reference velocity. The local climatology is introduced to deliver statistical data useful for designers.

The objectives of the new developments presented here are:

1. To extending the method to real complex buildings with many rooms
2. To include the indoor walls and doors into a simple network tool connected to the CFD main tool
3. To produce data useful to assess the indoor thermal comfort: air change rate, indoor velocity.

2 NUMERICAL APPROACH

2.1 *The CFD part*

The CFD method of UrbaWind consists in solving the Reynolds-Averaged Navier-Stokes equations on an unstructured rectangular grid with automatic refinement of the mesh in the vicinity of obstacles.

When the flow is steady and the fluid incompressible, those equations become:

$$\frac{\partial \rho \overline{u}_i}{\partial x_i} = 0 \qquad (2)$$

$$-\frac{\partial\left(\rho \overline{u}_j \overline{u}_i\right)}{\partial x_j} - \frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \rho\overline{u'_i\, u'_j}\right] + F_i = 0 \qquad (3)$$

The turbulent fluxes are solved by a one-equation model (transport equation for the turbulent kinetic energy) with a dissipation term deduced from mixing-length theory.

This methodology, along with the use of a very efficient multi-grid coupled solver allows to get fast convergence for every kind of geometry.

The turbulent viscosity μ is considered as the product of a length scale by a speed scale which are both characteristic lengths of the turbulent fluctuations. The speed scale is given as the square root of the turbulent kinetic energy multiplied by the density. The turbulent kinetic energy is solved using the transport equation by including the production and dissipation terms of the turbulence where the turbulent length scale L_T varies linearly with the distance at the nearest wall (ground and buildings).

$$\frac{\partial}{\partial x_i}\left[\rho \bar{u}_i k - \left(\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] = P_k - \varepsilon \text{ and } \mu_t = \rho k^{1/2} L_T \tag{4}$$

The production rate and the dissipation of the turbulent kinetic energy are calculated by

$$P_k = \mu_T \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_j}{\partial x_j} \text{ with } \varepsilon = C_\mu \frac{k^{3/2}}{L_T} \text{ and } C_\mu = 0.09 \tag{5}$$

Boundary conditions are automatically generated. The vertical profile of the mean wind speed at the computation domain inlet is given by the logarithmic law in the surface layer, and by the Ekman function. A 'Blasius'-type ground law is implemented to model frictions (velocity components and turbulent kinetic energy) at the surfaces (ground and buildings).

Typically CFD computation domains cover an area of 500 m x 500 m, allowing taking onto account the effects of neighbouring buildings. The mesh refinement at the obstacles can reach 10 cm. If needed, it is possible to compute simultaneously the flow inside the building, but with a high cost in terms of computation times and power.

2.2 *The Network part*

When using the Network approach, the internal pressure is not known and the flow rates through the openings are solved by an iterative process. Firstly the indoor pressure P_i is initialized as the average of the outer surface pressures P_k at the opening k, weighted by the square of the aerodynamic area A_k. The values of the P_k are obtained by the CFD calculation.

Then, the computation is made into two steps: at the iteration n, the flow rates at each opening k are computed by:

$$\left|Q_k^n\right| = A_k \sqrt{2\left|P_k - P_i^n\right| / \rho} \tag{6}$$

In a second step, the outflow rates are updated by solving the equation :

$$F(P_i) = \sum_k Q_k^n = 0 \tag{7}$$

with a Newton-Raphson iterative method (Deru and Burns, 2003), the internal pressure at step n+1 being calculated as :

$$P_i^{n+1} = P_i^n - \omega F\left(P_i^n\right) / F'\left(P_i^n\right) \tag{8}$$

where $F'(P_i)$ is the first derivative of $F(P_i)$ with respect to P_i , and ω is an under-relaxation coefficient. Then, the flow rates are adjusted with the new internal pressure. The iteration is stopped when the sum of flow rates $F(P_i)$, is inferior to 1% to the total of inflow rates.

In the case of a multi-volumes configuration, we distinguish the main room with multiple openings and the secondary rooms with only one door to the main room. Then, in the above formula, the aerodynamic surface of the opening k is replaced by an equivalent aerodynamic surface taken into account the door aerodynamic surface A_{door} with a formula quite similar than (1) :

$$A_k^{eq} C_k^{eq} = 1 / \sqrt{\frac{1}{A_k^2 C_k^2} + \frac{1}{A_{door}^2 C_{door}^2}} \quad (9)$$

2.3 *Example of application of the combined CFD-Network method: a simple detached house*

The building is a simple detached house (see figure 1) with an internal volume of 288 m^3 (length: 12 meters; width: 8 meters; height: 3 meters) and a slopping roof at 30°.

Previously to the natural ventilation calculation, CFD computations were made for 12 wind directions with a step of 30° (Fhassis *et al*., 2010). The upstream flow is a country side flow with a ground roughness z_0 about 0.05 m. The pressure field on façades and especially outside each opening was calculated for every wind direction (see figure 1 for a direction normal to the largest façade). The pressure coefficients at the middle of the external front wall, side walls, and rear wall are respectively Cp= 0.70, -0.4,-0.35) and are close to the values given in the "AIVC applications guide" for low rise buildings (Liddament, 1987).

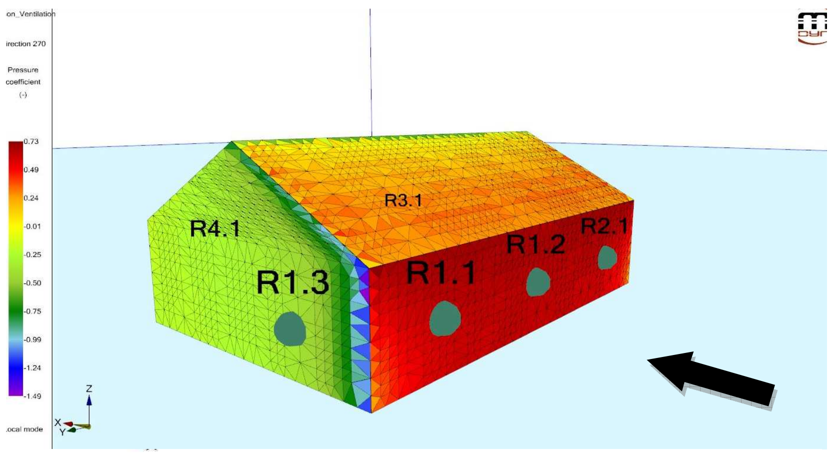

Figure 1: Pressure field on the façades and roof of a detached individual house. Openings are represented in grey.

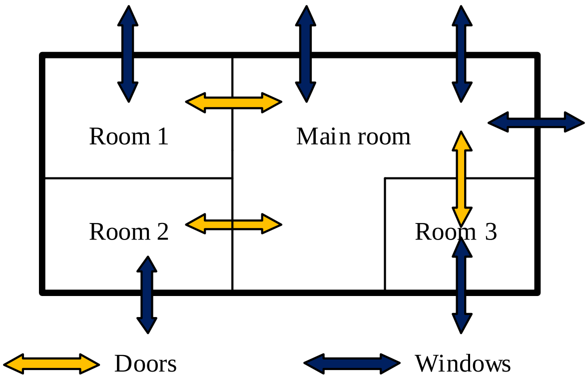

Figure 2: Openings (doors and windows) of the detached house

The building house was considered first without any internal walls (6 windows) and secondary, in a more realistic way, by including internal walls and doors (6 windows, 3 doors) as shown on figure 2.

In order to qualify the cross flow, for this example, all the wind directions had the same level of occurrence and the average wind speed was 2 m/s at 10 m above the ground. So the average air change rate of each rooms and for the whole building was computed with the new ventilation tool of UrbaWind (ACH).

The ACH are given in the table 1 for each room with windows area of 2 m² and doors area of 2m². The table 2 gives the ACH of the building for various internal porosity ratio : ratio between windows area A_W and doors area A_D for rooms. As observed on the table 1, the main room ventilation is the less dependent on the internal porosity because it is cross ventilated itself. On the other hand, the secondary room ventilation depends on the door area devoted to the cross ventilation. When A_D is twice A_W, the influence of internal wall is less than 10% but if they are equal the reduction can reach 20% for the whole volume or more than 30% for the secondary room compared to the full cross ventilation configuration. With the windows area twice the doors area, the reduction of efficiency is about 30% in our case. Hence ventilation design guide recommends designing bioclimatic buildings with at least an internal porosity equal to the external wall porosity.

The tool becomes useful to extract the ACH by integrating both the internal fitting:

Table 1. Influence of the internal walls on ACH of each rooms : A_W=2m² A_D=2m²

	Main room	Room 1	Room 2	Room 3	Building
ACH (vol/h) without internal walls	21.4	6.7	9.0	9.0	45.9
ACH (vol/h) with internal walls and doors	20.0	4.6	6.6	6.6	37.7
Difference (%)	-7%	-31%	-26%	-26%	-18%

Table 2. Influence of the internal walls on the building ACH for various internal porosity

	A_W=1m²	A_W=2m²	A_W=4m²
Porosity ratio for cross ventilated room	200%	100%	50%
ACH (vol/h) without internal walls	27	46	80
ACH (vol/h) with internal walls A_D=2m²	25	37	55
Difference (%)	-7%	18%	-31%

3 COMFORT OF A NATURALLY VENTILATED SCHOOL (FRENCH GUYANA)

The project concerns a secondary school in Kourou (figure 3). Architect designed the classroom's walls as porous walls with Jalousie windows. The classrooms buildings (West side) could be under ventilated because of the main buildings influence (East side).

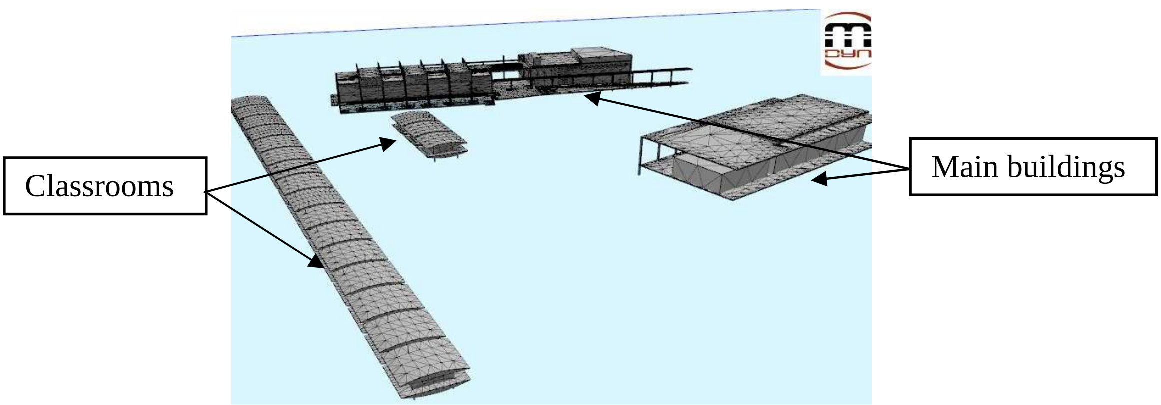

Figure 3: Geometry of the secondary school project

In French Guyana close to the equator, trade winds are not so strong. The climatology behaviors estimated at 10m above the ground where the project will take place was computed from the meteorological mast with the software TopoWind (©). The average velocity is close to 3 m/s. A statistical analysis of the histogram shown in figure 4 was carried out. At the middle height of the building façade (1.5 m above the ground), the velocity exceeds the value of 1 m/s 80% of the time. Hence according to the guide dedicated to the natural ventilation of buildings in warm tropical climate (Gandemer *et al.*, 1992) the building could be natural ventilated in this place. But due to the close neighbouring buildings, the wind has to be computed and the mass flow rates entering the classrooms have to be assessed.

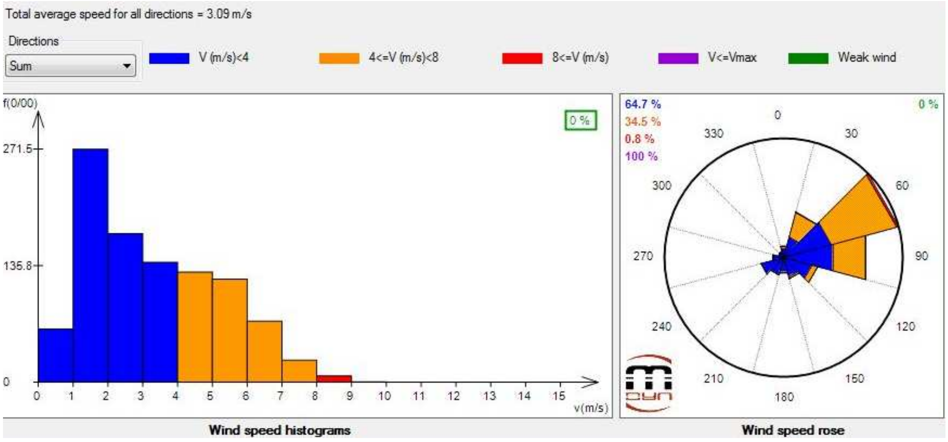

Figure 4: Climatology at the site (10 m above the ground)

The wind flow simulations were carried out for each wind incidences from 0° to 330° with a step of 30°. The figure 5 shows an example of the pressure coefficient field for the trade wind direction in Guyana (“Alizées” trade wind blows in the sector 70°-80°).

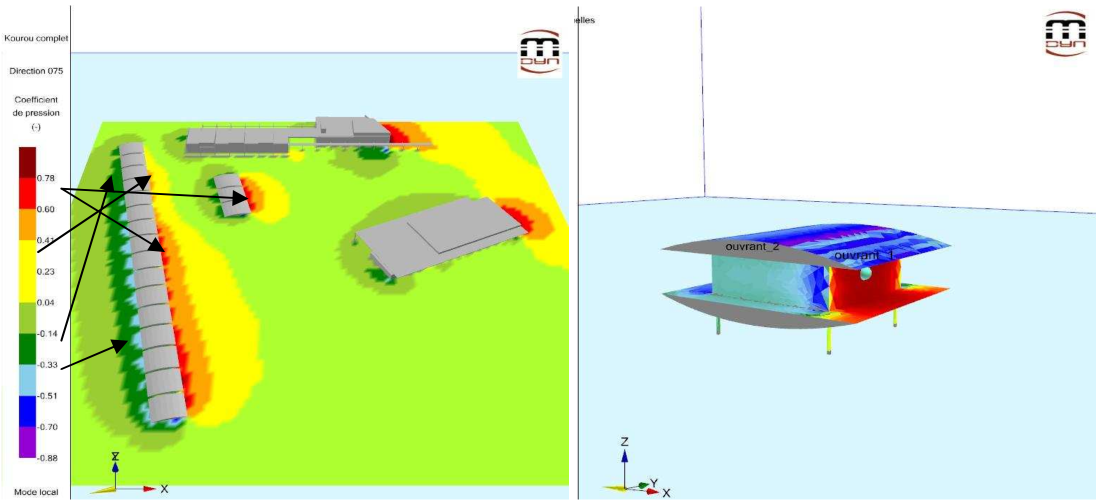

Figure 5: View of the secondary school and pressure coefficient field on an horizontal plane 4 meters above the ground (left) and on the walls of a classroom (right)

For each set of pressure, the flow rate was evaluated following the macroscopic method described previously. The wall porosities of the east and west façades was 20%. The real ventilation was estimated for the real climate around the school by taking into account the occurrence of every couple velocity/incidence (Figure 6). The yearly average ACH for the less ventilated classrooms was close to 120 vol/h. Further post processing shows that during 2 weeks a year, in summer, ACH is lower than 30 vol/h. It was expected from experiences that 30 vol/h was not enough to extract sufficiently the indoor heat. Usually 50 vol/h is the minimum value required in this tropical area and wall porosity has to be increased to 30% at least. Hence, only during 2 weeks a year, ACH will be lower than 50 vol/h. This value could used to design the building envelope according to the thermal response of the building. Thermal comfort would be achieved the remaining of the time (more than 96 % of the time).

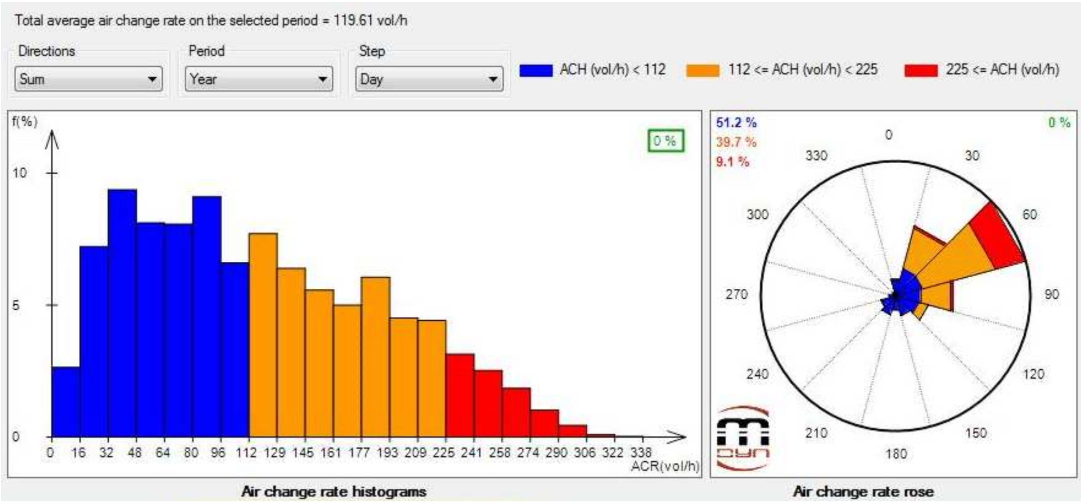

Figure 6: Air change rate ACH of the classroom: histogram and rose (yearly data)

In order to evaluate the indoor thermal comfort, the velocity computations were carried out inside the classrooms to extract a relation between the average velocity at the openings inlet section and the velocity inside the room into the main stream tube. Curves in figure 7 are in accordance with experimental data for a simple building (Karava *et al.*, 2010). The ratio of the mean and the gust indoor velocities versus the mean velocity throw the window section are respectively close to 0.50 and 0.70 in space average. The minimum values are respectively close to 0.40 and 0.50.

The combined CFD-network deduces from each mass flow rate throwing the rooms the indoor velocity.

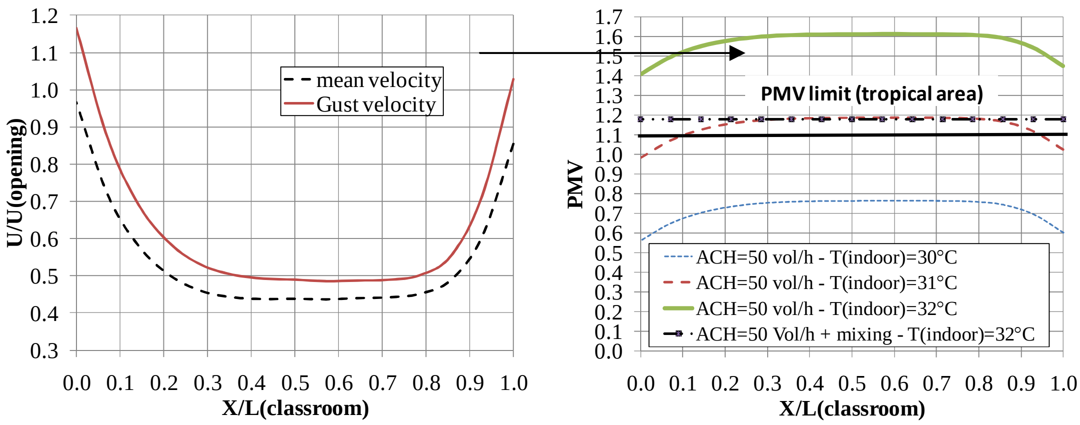

Figure 7: velocity on the center line between the inlet and outlet openings - PMV index in the classroom

The PMV index was calculated according to the indoor temperature T_{indoor} and the indoor velocity V_{indoor} and compared to the maximum value of 1.1 (Wang, 2006).

$$PMV = -11.7853 + 0.4232 \times T_{indoor} - 0.57889 \times V_{indoor} \qquad (10)$$

$$\text{With } V_{indoor} = 0.5 \times V_{inlet} = 0.5 * \frac{\text{ACH} \times \text{Volume of room}}{S_{\text{opening}} \times 3600} \qquad (11)$$

If ACH is higher than 50 vol/h then the mean overheating temperature may not exceed two degrees as soon as the thermal insulation is adapted to the tropical climate. Hence, as an example, the PMV was estimated inside the classroom (figure 7). With a space averaged value given by the formula (11), the average PMV index is 0.7, 1.1 and 1.5 for T_{indoor} equal respectively to 30°C, 31°C and 32°C. If ACH reach 100 vol/h, the PMV index becomes 0.5, 0.9 and 1.3. That means if the wind is not enough strong to generate comfortable cross flow, additional mixing has to be generated with ventilator fitted on the ceiling. With this equipment, PMV is reduced for T_{indoor} at 32°C at 1.2 for ACH=50 vol/h. It is close to a comfortable situation.

Given the strong influence of the indoor temperature on the comfort parameter, further thermal analyses have to be conducted in order to achieve the thermal comfort by including the real temperature and insulation scenario in summer when the secondary school will be opened.

4 CONCLUSION

Natural ventilation is less effective in urban environment and not easy to be designed because of the complexity of wind velocity behaviors. Hence air exchanges across the buildings openings are function of the wind speed in the urban area, of the building shape and on the openings efficiency. Designers have to validate the choice of openings (positions, dimensions and efficiency) in order to enhance cross natural ventilation and to allow a good air quality and thermal comfort. In this context, the software Urbawind was upgraded to introduce a cross ventilation tool based on a mixed CFD-Network approach. The software first computes the pressure fields on the building for every wind incidence with the wind reference velocity, then evaluates air exchanges for each climatology event and finally builds statistical data of the air exchanges as inputs for thermal tools.

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