Potential and limits of Natural Ventilation for comfort in retrofit buildings in tropical climates

Brieg Riou[1*], *Egoï* Ortego[1], *Valentin* Delplanque[2], *Benoit* Blanchard[2], *Jacques* Gandemer[3], *and Pascal* Stabat[1]

[1]Mines Paris, PSL University, CES, 60 Bd St Michel 75006 Paris, France
[2] Laboratoire Aérodynamique Eiffel, Paris, France
[3]JGConseil, Sucé sur Erdre, France

Abstract. The space cooling demand is growing very fast in the world in conjunction with the increase of life standards and the climate change. A major stake for the future in buildings is to provide human comfort and to limit the cooling energy consumption. In this context, natural ventilation turns to be an interesting solution in tropical zones where 40% of the world's population lives. This paper aims to assess the potential and limitations of wind induced crossed natural ventilation for comfort in tropical environments. A method based on correlations from the literature is proposed, integrating all the links in the physical chain of natural ventilation, i.e. from outdoor climatic conditions to indoor comfort. The application of this method is done through a case study in Reunion Island and gives orders of magnitude of comfort time proportion according to different parameters such as the opening surface, the indoor thermal and humid loads and the orientation of the considered building. Finally, the limitations of the method are discussed, as well as the need for research to define design rules to favour natural ventilation for housing and office retrofit.

1 Introduction

The International Energy Agency (IEA) [1] notes a threefold increase in final energy consumption for air conditioning in commercial and residential buildings compared to 1990, amounting to 2,020 TWh in 2016. The summer comfort is a major stake for the future, in particular, in tropical climates where cooling needs are high. The number of air conditioners is expected to increase strongly, according IEA [1], with projection to 5.58 billion units in 2050 against a stock of 1.621 billion units in 2016. The air conditioning contributes to climate change through GHG emissions caused by the leakage of refrigerants charged into the equipment and the electricity consumed to operate the equipment.

In this context, natural ventilation can be an interesting alternative to air conditioning in intertropical zones where 40% of the world's population lives and trades wind are strong and regular.

To consider passive cooling by natural ventilation of buildings in tropical environments, several conditions must be met. One of the main obstacles to natural ventilation is the noise in the vicinity of the building. Moreover, the management of privacy and risks of infraction can be managed by blinds and mosquitoes by screens but to the detriment of the natural ventilation rate. Katsoulas et al. [2] found that insect nets equipped on openings caused a 33% reduction of ventilation rate in a Greenhouse. If the environmental noise conditions are satisfactory, it is then essential to analyse whether the wind at the building site is significant and very frequent.

A key issue with natural ventilation is to assess the conditions to reach acceptable thermal comfort. Abdessellam [3] has built a thermal audit of naturally ventilated housing, based on a simple and measurable indicator: the degree of overheating between interior and exterior. It allows to check the good design of the building with regard to solar protection and natural ventilation (overheating $< 2\,°C$). However, low overheating is not a sufficient condition for thermal comfort, which also depends on the temperature and humidity level outside.

First, this paper presents the external conditions that are the wind as a force and the urban environment as a constraint to natural ventilation. Then, a simple method is proposed to evaluate the potential and limits of natural crossed ventilation for comfort. Finally, the limits of the method and the need for future work are discussed.

2 Wind and urban environment conditions for natural ventilation

This research is based on a case study on the island of Reunion, a French overseas department, located in the Indian Ocean off Madagascar. More specifically, the study is based on weather data measured over the full year 2015 at the Pierrefonds weather station in west of the island [4]. These data include wind speed and direction, air temperature and air humidity on an hourly basis.

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[*] Corresponding author: brieg.riou@minesparis.psl.eu

A pre-processing of the data was carried out in order to remove faulty measurements: missing data 1.53%; wind speed measurements outside the measurement range of the sensors 0.37%. The latter are assumed to be negligible in the assessment of comfort over a full year since they are not consecutive. A total of 166 hours of measurements were removed, of which 151 were for the austral summer period and 15 for the austral winter.
Indeed, two seasons are distinguished: the austral summer, which runs from November to April, is the hottest and damper season; the austral winter, which begins in May and ends in October, is comparatively cooler. **Fig. 1** gives the average temperature per hour for each of these seasons, as well as the average temperature difference between day (8am - 9pm) and night (10pm - 7am) during the austral summer. Two major observations can be made. Firstly, the cooling issues are concentrated in the summer season, where the average temperature is 3.5°C higher than in winter. Secondly, the temperature difference between day and night in summer is 3.4°C which is quite low making the night coolness storage rather inefficient. Moreover, buildings in tropical climates are generally built with little mass, which further reduces the storage capacity. A continuous ventilation strategy is therefore preferable.

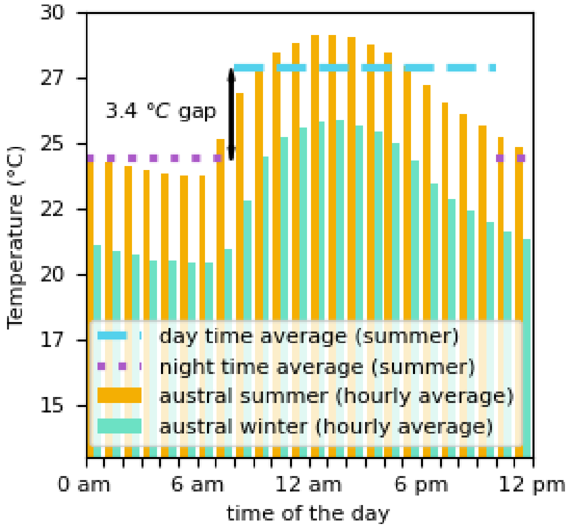


Fig. 1. Hourly average temperature per season

2.1 Wind potential in tropical climates urban environment

The wind speed data is taken from a weather station located at Pierrefonds airport on the seafront, which is an open area. The presence of obstacles such as buildings or vegetation will however disturb the flow and lead to lower wind speeds. A readjustment of the meteorological wind data is necessary to adapt them to an urban area.
The norm on wind action [5] gives a method taking into account the roughness of the original terrain as well as the roughness of the target site and the altitude at which the wind speed is to be known. Considering only the variation due to the modification of the terrain roughness, i.e. in the absence of altitude variation and too imposing obstacles, the expression is written:

$$V_{loc}(y) = V_{ref} \times C_r(y, y_0) \qquad (1)$$

$$\mathrm{C_r}(\mathrm{y}, \mathrm{y_0}) = 0.19 \times \left(\frac{\mathrm{y_0}}{\mathrm{y_{0,II}}}\right)^{0.07} \times \ln\left(\frac{\mathrm{y}}{\mathrm{y_0}}\right) \qquad (2)$$

Assuming a target terrain roughness of $y_0 = 0.5$ m (corresponding to an urbanised or industrial area) and approximating the original terrain roughness to $y_{0,II} = 0.05$ m (open country), the roughness coefficient at height $y = 10$ m (height of weather station measurement) is $C_r(y, y_0) = 0.67$. In the following, the considered wind signal has been reduced by 33%.
The **Fig. 2** gives the number of summer days for which the average wind velocity is below a given value. Three periods are considered: day time, night time and the entire day. The number of summer days for which the wind velocity daily average is below a 2 $m.s^{-1}$ threshold is only of 38 considering the entire day, and 25 considering only day time. However, the night wind regime appears to be somewhat less favourable, which means that the thermal comfort for this period must also be studied.

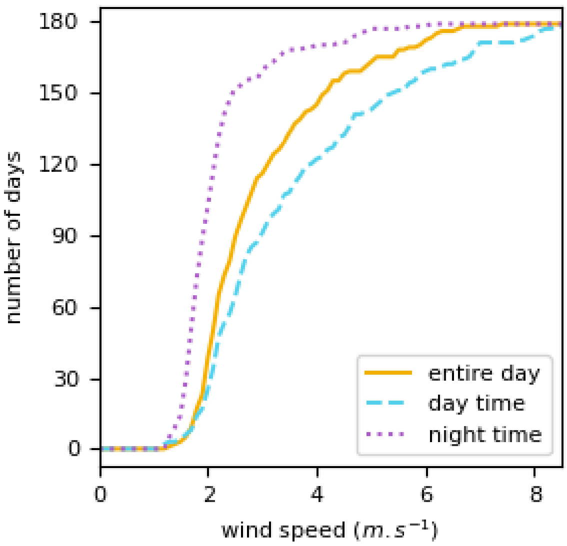


Fig. 2. Number of summer days for which the average wind speed is below a given value

The natural ventilation potential also depends on the regularity of the wind direction, in the sense that the pressure field generated by the wind around a building depends on the angle of incidence of the wind. The wind roses calculated for the summer day (**Fig. 3** (a)) and summer night (**Fig. 3** (b)) periods show two wind directions. The first one from south-east corresponds to the sea breeze blowing during the day (a), at night the land gives off heat resulting in an onshore breeze blowing from a north-north-east direction (b). The wind directions for the winter season are similar.

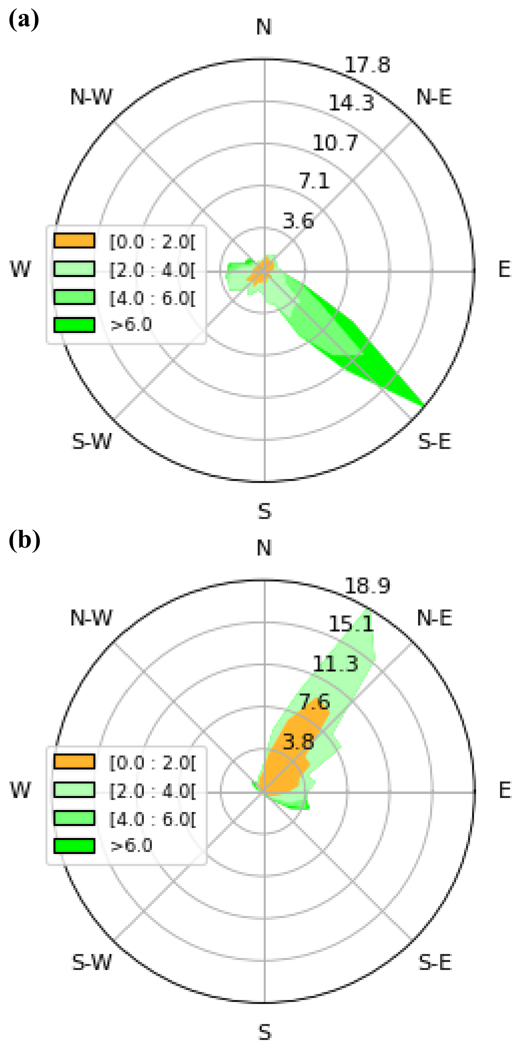


Fig. 3. Wind roses for summer daytime (a) and night time (b) hours

2.2 From pressure coefficients on building façades to air flow rates

In cross ventilation, the effect of wind is the main driver of air movement. Correlations introduce a direct relationship between dynamic pressure and air change rate.

Etheridge and Sandberg [6] show that this rate can be related to the pressure difference between the two façades. For a given building and environment, the pressure difference increases with the square of the wind speed. One introduces a pressure coefficient ΔC_p expressed as the ratio between the pressure difference between both façades and the dynamic pressure of the wind at a reference height, v_{ref}, as follows:

$$\Delta C_p = \frac{2\Delta p}{\rho {v_{ref}}^2} \qquad (3)$$

The air change rate due to wind when the openings on both sides of the building have the same area can be expressed as [6]:

$$\dot{V} = \mathrm{C_d A v_{ref}} \sqrt{\frac{\Delta \mathrm{C_p}}{2}} \qquad (4)$$

with C_d the discharge coefficient, always considered in the air change rate calculation as 0.61, which is common for small opening surface [7].

Many references state empirical or semi-empirical methods to calculate the ΔC_p coefficient based on building environment and wind incident angle [8–11]. Rousseau and Mathews [11] propose the following formula for the calculation of C_p dependent of the wind incident angle θ:

- For $\theta \leq 90°$ *and* $\theta \geq 270°$:

$$\begin{aligned} C_p(\theta) =\ & 0.5994 - 0.1426\,|\,sin(\theta)\,| \\ & - 0.8055\,|\,sin(\theta)\,|^2 \\ & + 2.0149\,|\,sin(\theta)\,|^3 \\ & - 2.1972\,|\,sin(\theta)\,|^4 \end{aligned} \qquad (5)$$

- For $90° < \theta < 270°$:

$$\begin{aligned} C_p(\theta) =\ & -0.33300 - 0.1544\,|\,sin(\theta)\,| \\ & - 0.1128\,|\,sin(\theta)\,|^2 \end{aligned}$$

ΔC_p is calculated as the difference between the pressure coefficients at the front and back of the building.

As reported in [12], the correlations (5) assume homogeneous pressure distribution over the building façades which can be an uncertainty source to the calculation.

Furthermore, correlations (5) were obtained for an isolated building. Delplanque [13] showed that the ventilation potential ΔC_p is reduced by its urban environment : maximum ΔC_p corresponding to a zero wind incident angle are given depending on the properties of the upstream urban area. For ground occupation rates of 10% and 23%, Delplanque [13] obtained ΔC_p values of 0.52 and 0.30 respectively.

2.3 Comfort level and wind speed

Givoni [14,15] proposed a diagram of comfort based on temperature, humidity and speed of air the upper assuming that limits of accepted temperature and humidity are higher for people acclimatised to hot and humid conditions. At equivalent temperature and humidity, the presence of an air speed between 0.5 and 1.5 $m.s^{-1}$ makes it possible to improve the temperature felt by people exposed to this air flow. The Givoni diagram [14,15] was established on a psychrometric chart, for a sedentary activity and with clothing adapted to the summer. Widely used in South America and in the French overseas departments and territories, it has been the subject of studies conducted by the PIMENT laboratory at the University of Reunion and revalidated by a series of surveys on non-air-conditioned buildings (Lenoir Thesis [16]). Lenoir [16] proposes a new comfort zone, which is not associated with a specific air speed considering that air speed above 1 $m.s^{-1}$ carries to much of a risk of discomfort. However, it is assumed that the natural and mechanical (ceiling fans) ventilation of the building is properly sized. In the following, discomfort is assessed according to the proposed Lenoir criterion [16].

Due to the thermal and humidity loads within the building that affect the feeling of comfort, it is not sufficient to assess the comfort level from external data. A correction must be made for temperature and humidity. Outdoor temperature variations are small (less than 0.7°C on average from one hour to the next), and buildings in tropical climates have little inertial capacity. An instantaneous equation model without consideration for inertia seems sufficient. Moreover, given the importance of natural ventilation exchanges, losses through the envelope are neglected.

2.3.1 Temperature increase

Since the dry air mass flow rate is conserved, the heat balance can be written as follows:

$$\begin{aligned}&(\dot{m}_{dry\ air}C_{p,air} + \dot{m}_{dry\ air}w_{ext}C_{p,water\ vapour})\\ &\times T_{ext} + \dot{Q}_s\\ &= (\dot{m}_{dry\ air}C_{p,air}\\ &+ \dot{m}_{dry\ air}w_{int}C_{p,water\ vapour}) \times T_{int}\end{aligned} \tag{6}$$

Where $\dot{m}$ denotes a mass flow rate in $kg.s^{-1}$, C_p a heat capacity at constant pressure in $J.K^{-1}kg^{-1}$ and T an air temperature in K. The term $\dot{Q}_s$ denotes the instantaneous internal sensible heat input and is expressed in W. w designs the specific humidity defined as the ratio of the mass of water vapour to the mass of dry air.

Neglecting the difference in humidity between interior and exterior, the temperature difference $\Delta T = T_{int} - T_{ext}$ can be expressed for an average specific humidity $w_{average}$ as:

$$\Delta T = \frac{\dot{Q}_s}{\dot{m}_{dry\ air}\left(C_{p,air} + w_{average} \times C_{p,water\ vapour}\right)} \tag{7}$$

And can be simplified as follows:

$$\Delta T = \frac{\dot{Q}_s}{\dot{V} \times \left(C_{p,humid\ air} \times \rho_{humid\ air}\right)} \tag{8}$$

Where $\rho_{humid\ air}$ is the mass density of humid air in $kg.m^{-3}$. The product $C_{p,humid\ air} \times \rho_{humid\ air}$ is taken constant and equal to 1,184.9 $J.K^{-1}.m^{-3}$ (calculated for a medium air temperature and a relative humidity of 27°C and 70% respectively).

2.3.2 Humidity increase

Again neglecting inertia and envelope losses the instantaneous humidity balance can be written as:

$$w_{ext} \times \dot{m}_{dry\ air} + \frac{\dot{Q}_l}{\Delta H_{vap}} = w_{int} \times \dot{m}_{dry\ air} \tag{9}$$

The term $\dot{Q}_l$ refers to the instantaneous internal latent heat load and is expressed in W. The water latent heat of vaporisation ΔH_{vap} is considered to be independent of the air temperature in the interval of interest. The selected value is 2,44I.7 $kJ.kg^{-1}$ corresponding to an air temperature of 25 $°C$. The specific humidity difference between interior and exterior $\Delta w = w_{int} - w_{ext}$ is obtained from (9) as follows:

$$\Delta w = \frac{\dot{Q}_l}{\Delta H_{vap} \times \dot{m}_{dry\ air}} \tag{10}$$

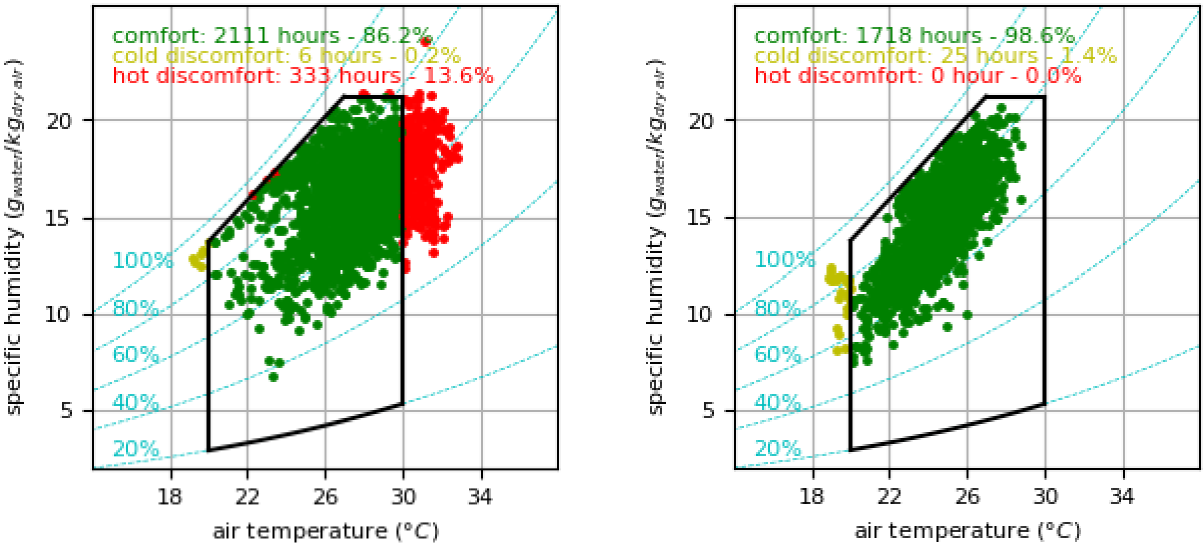
2.4 Thresholds

The case study is that of a flat with Depth/Width/Height of 10× 10× 2,5 m^3. The windward and leeward openings have the same area, the equation (4) applies.

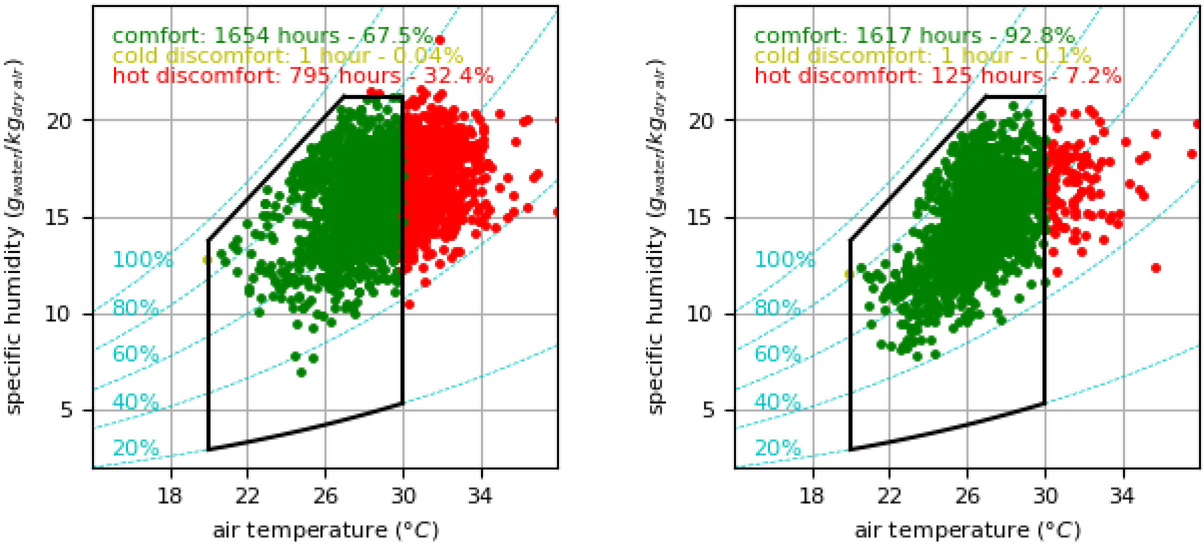
Fig. 4 (a-e) plot the indoor humidity and temperature data calculated from equations (8) and (10) for the southern summer season on a psychrometric chart and assess comfort according to the Lenoir criterion (comfort zone delimited by the frame) [16]. The points strictly within the limits of the zone proposed by Lenoir [16] correspond to hours for which there is supposedly thermal comfort. The points outside the zone correspond to discomfort. A distinction is made between two cases depending on the temperature: cold discomfort at 20°C or under and hot-humid discomfort over 20°C. Cold discomfort is considered to be manageable supposing that the heat loads are sufficient to increase inside temperature with closed windows.

The surface heat loads considered are $\dot{Q}_s = 10\ W.m^{-2}$ and $\dot{Q}_l = 2.5\ W.m^{-2}$, and a façade orientation of 130° (taken from the north by convention) is assumed, which corresponds to an alignment with the most frequent wind direction during the day (**Fig. 3** (a)).

(a) **daytime** - $\dot{Q}_s = \dot{Q}_l = 0\ \mathrm{W.m^{-2}}$ (outdoor) **(d)** **night time** - $\dot{Q}_s = \dot{Q}_l = 0\ \mathrm{W.m^{-2}}$ (outdoor)



(b) **daytime** - $\dot{Q}_s = 10\ \mathrm{W.m^{-2}}$, $\dot{Q}_l = 2.5\ \mathrm{W.m^{-2}}$ - *porosity = 4%.* **(e)** **night time** - $\dot{Q}_s = 10\ \mathrm{W.m^{-2}}$, $\dot{Q}_l = 2.5\ \mathrm{W.m^{-2}}$ - *porosity = 4%.*



(c) **daytime** - $\dot{Q}_s = 10\ \mathrm{W.m^{-2}}$, $\dot{Q}_l = 2.5\ \mathrm{W.m^{-2}}$ - *porosity = 20%.* **(f)** **night time** - $\dot{Q}_s = 10\ \mathrm{W.m^{-2}}$, $\dot{Q}_l = 2.5\ \mathrm{W.m^{-2}}$ - *porosity = 20%*

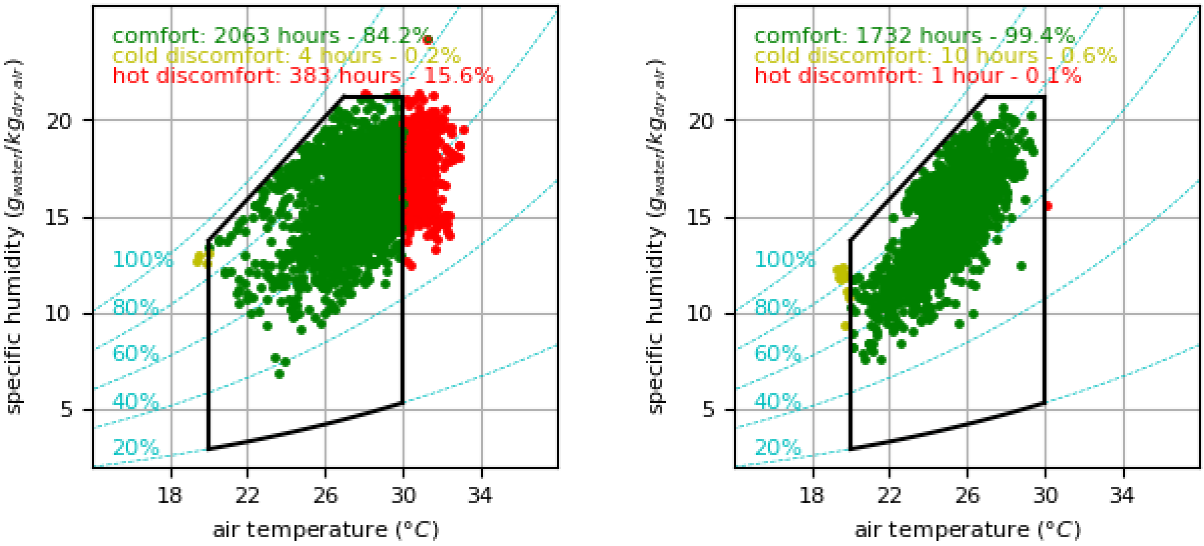


Fig. 4. Simulated summer data ploted on a psychrometric chart assessing comfort according to Lenoir's criterion [16]

Fig. 4 (a-c) refer to daytime hours while **Fig. 4** (d-f) refer to night time hours. For each of these periods, three identical cases are presented:

1. **Fig. 4** (a,d): Humidity and temperature are taken equal to the weather data for the outside. This case corresponds to a limit that cannot be crossed by natural ventilation alone since the objective of natural ventilation is to limit overheating between the interior and the exterior. This is at least the case for an evaluation of comfort in the sense of Lenoir's criterion [16] without relying on the inertia of the building to dampen heat peaks.
2. **Fig. 4** (b,e): Façade porosity of 4% - is an attempt to represent low natural ventilation. Taking a lower porosity would have resulted in very low flow rates making the no inertia assumption not applicable.
3. **Fig. 4** (c,f): Façade porosity of 20% – is an attempt to represent effective and feasible natural ventilation.

In spite of a weaker wind signal and a less favourable orientation (façade orientation is 130° whereas the most frequent wind direction is 30°) the night-time comfort can be ensured almost the whole season with a porosity of 20% (only 1 hour of discomfort) **Fig. 4** (f). On the contrary, a low natural ventilation still results in a proportion of discomfort hours of 7.2% (**Fig. 4** (e)).

For the daytime in summer, the calculations show a minimum proportion of 13.6% discomfort **Fig. 4** (a). The number of discomfort hours in the summer daytime is more than halved with a porosity of 20% compared to a porosity of 4% (15.6% discomfort hours (f) compared to 32.4% (e)), which accounts for the potential of natural ventilation.

Similar calculations were performed for the austral winter period which resulted to only 9 hours of thermal discomfort during daytime (0.4%) and none during night time, which confirms that comfort issues are concentrated in the summer season.

Fig. 5 (a-b) show the result of a parametric study to investigate the effect of façade orientation and maximum ΔC_p values (a) and sensible and latent heat loads (b) on the number of hours of discomfort (according to Lenoir's criterion [16]) as a function of façade porosity (range 4% - 32%). The thermal and humidity loads for (a) are the same as for **Fig. 4**, the façade orientation for (b) is 130°. The dotted lines in **Fig. 5** (a) were calculated integrating ΔC_p corrections for the effect of the built environment from:

$$\Delta C_{p,corrected}(\theta) = \frac{\Delta C_p(\theta) \times \Delta C_{p,max}}{\Delta C_p(0)} \tag{11}$$

The maximum values $\Delta C_{p,max}$ considered were 0.52 and 0.30 as described in Section 2.2.

All curves converge towards an asymptote of 333 hours corresponding to the minimum number of discomfort hours achievable by natural ventilation as identified with **Fig. 4** (a). **Fig. 5** (a) shows that the orientation of the façade has little influence on the number of discomfort hours and even becomes quite negligible from a façade porosity of about 13%. On the contrary, the effect of internal loads is significant and persists beyond a porosity of 30% (**Fig. 5** (b)). This difference can be explained by the fact that ΔT (8) is proportional to the heat load but is only inversely proportional to the root of ΔC_p, which depends on the wind angle.

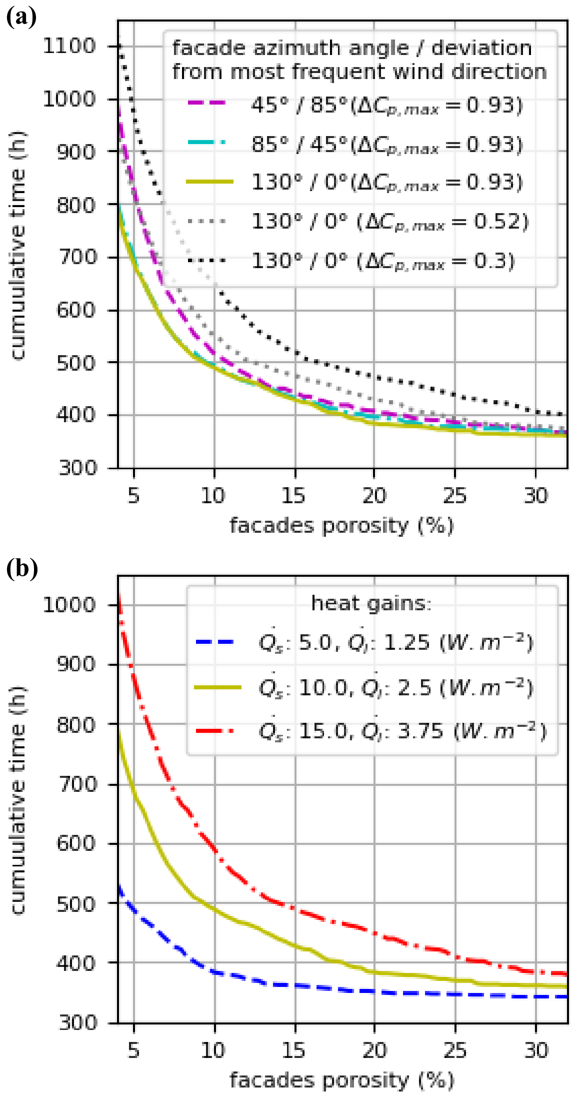


Fig. 5. Number of hours of thermal discomfort as a function of façades porosity during summer days for various façade azimuth angles and ΔC_p maximum values (a) and internal loads (b). (a): $\dot{Q}_s = 10\ W.m^{-2}$, $\dot{Q}_l = 2.5\ W.m^{-2}$. (b) : façade angle = 130°.

3 Discussion

The assessment of comfort in naturally ventilated buildings is very complex. A simplified method has been developed providing orders of magnitude of indoor comfort. It shows the whole chain of calculation from meteorological data including temperature, humidity, wind speed and direction up to the comfort evaluation. On each step of calculation, assumptions can be discussed:

Meteorological data

In the context of global climate change, average temperatures as well as the frequency and intensity of heat peaks are likely to increase. Realistic climate scenarios reflecting climate change should be built.

Moreover, the wind data is generally given from weather stations close to airports and therefore away from studied buildings. Consequently, the wind signal at the vicinity of the studied building should be recalculated considering the roughness of the built-up area upstream. The roughness to be considered obviously varies according to the urban environment around the building and the direction of the incident wind which can vary according to the time of day. The methods for readjusting the amplitude of the wind signal also assume a full development of the boundary layer, which is not necessarily the case when the distance travelled by the wind in the urban area before encountering the building is too small.

Pressure coefficients

There is a substantial literature on the calculation of ΔC_p but it does not cover all situations. The Matthews and Rousseau correlation *(5)* used to obtain façade pressure coefficients has the advantage to include the influence of wind incidence but does not take into account the shape of the building or the position of interest on the façade (altitude and proximity of edges).

Calculation of parameters for comfort assessment

The approach in this study is based on static heat and humidity balances without considering building inertia. Even if the day/night temperature variations are quite low, dynamic simulations could be carried out to account for indoor temperature smoothing by wall storage. In addition, more realistic internal load and occupant scenarios could be added instead of constant loads all day long. Moreover, considering a single zone is also reductive. First of all, the interior layout and partitioning define priority flow zones for which the convective exchange coefficients (both with the occupants and the radiating masses) are more important to the detriment of 'dead' zones.

Indoor comfort criteria

Concerning the assessment of comfort, the criterion developed by Givoni [14,15] and modified by Lenoir [16] follows a binary conception of comfort. No consideration is given to the intensity of discomfort. An evaluation of discomfort for a given point taking into account the ‘distance to domain boundaries’ by translating temperature and specific humidity differences into enthalpy equivalents could be imagined. In addition, the surveys on which Lenoir's criterion [16] is based were carried out during daytime, so the conception of thermal comfort at night may differ. Furthermore, the method used here assumes the local velocities are properly adjusted for comfort, by using air blowers if necessary. In case of too high local velocities ($> 1 m.s^{-1}$) causing discomfort, it is also assumed the occupants to adjust the openings reducing the effect of natural ventilation. Little consideration is given to the link between local air velocity and indoor temperature for comfort.

Internal Partitions and façade porosity

Furthermore, the pressure coefficients on the façades used for natural ventilation flowrate calculation do not take into account the local interactions between the interior and the exterior, which can vary notably according to the direction of incidence of the wind. Many issues have not been addressed to date. How loggias, balconies, shutters, mosquito nets on the opening can impact the ventilation flow rate? How the interior layout and partitioning can impact the ventilation flow rate?

4 Concluding remarks

The assessment of comfort in naturally ventilated building raises many questions. Computational Fluid Dynamics and dynamic building thermal simulation can provide a thorough analysis but it requires a lot of expertise and is very time-consuming in such a way that they are usually not used for building design and in particular for building retrofit. In retrofit of buildings, the main design actions are related to facade porosity and internal partitions.

The simple method proposed in this paper is useful as preliminary assessment of the natural ventilation potential in tropical climates. First of all, the climatic data should be assessed as shown in the case study of the building in La Réunion island. The analysis of Pierrefonds weather data has shown a minimum proportion of summer day time thermal discomfort of 13.6%. This rate is calculated considering zero indoor-outdoor overheating and constitutes a threshold that cannot be overpassed by natural ventilation alone in the absence of inertial phenomena.

However, further research is necessary to define design rules for building retrofit, as discussed in Section 3

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