Chapter

Fundamentals of Natural Ventilation Design within Dwellings

Ivan Oropeza-Perez

Abstract

Along with acoustical and lighting comfort, indoor air quality (IAQ) and thermal comfort upon households are essential to maintain a proper indoor environment, therefore ensuring a welfare toward the occupants. Nevertheless, sometimes, these features are neglected by building designers and constructers, causing problems such as the so-called sick building syndrome (SBS) and thermal discomfort, among others. Although there are short-term solutions such as purifiers, extractors, fans, and air conditioning, eventually these methods become not sustainable activities that consume energy and emit polluting gases such as chlorofluorocarbons. One alternative to this is natural ventilation, understood as the airflow throughout a building caused by changes of pressures naturally produced. In this chapter, the role of the early-stage building design as well as the correct occupant behavior is presented as essential to develop a naturally ventilated dwelling, which is an excellent alternative to achieve proper levels of indoor environment in a sustainable manner.

Keywords: natural ventilation, indoor air quality, thermal comfort, early-stage design, occupant behavior

1. Introduction

For the coming years, the so-called climate change will be a great challenge to be faced by the human kind, being the activities of this very same specie the most influencing factor for its rapid growth in the last decades.

One of these activities is the electricity generation, which in order to be produced, in many cases, a fossil fuel has to be burned. According to the International Energy Agency, “in 2016, generation from combustible fuels accounted for 67.3% of total world gross electricity production” [1] causing the emission of greenhouse gases and thus increasing the global warming.

In this context, according to the Intergovernmental Panel on Climate Change (IPCC), the building sector is an important target for the climate change because it accounts for almost 40% of the total energy use, embracing almost 25% of the global greenhouse gases emissions [2].

One of the most energy-consuming activities within the buildings is the space conditioning, in order to achieve proper levels of illumination, acoustics, indoor air quality (IAQ), and thermal comfort. For IAQ and thermal comfort, strategies of heating, ventilation, and air conditioning (HVAC) are applied by using fans, air-conditioning systems, and radiation systems, among others. These strategies, however, generally imply a high-energy consumption, including electricity. Moreover, IAQ and space cooling strategies use generally electricity for running fans, air-conditioning systems, evaporative coolers, air purifiers, air extractors, and air filters. According to Ekwall, only air-conditioning for cooling could account for more than half of the residential electricity usage of a single household located in a developing country with warm conditions [3].

Furthermore, if thermal comfort and IAQ are not achieved, especially in warm to hot countries, problems such as the sick building syndrome (group of symptoms of the occupants due to not-ventilated buildings such as dizziness, nausea, irritation, cough, itching skin, allergies, and headache [4]) and cold, flu, and other problems caused by high indoor temperatures could be arisen.

Therefore, strategies that do not imply high electricity consumption should be applied to achieve proper levels of IAQ and thermal comfort in warm to hot conditions. In this context, the usage of natural ventilation is proposed as a solution to these challenges while maintaining low levels of electricity use.

2. Fundamentals of natural ventilation

Natural ventilation within buildings is understood as the airflow throughout the construction propelled by pressure changes naturally produced. These pressure changes, or driving forces, are mainly two: wind pressure and buoyancy [5]. Both changes have the same physical origin but in different scales.

Wind pressure is defined as the wind incidence onto a building façade at a certain velocity and direction. When the wind impinges the façade, a positive pressure (or windward) occurs, while in the opposite façade of the building, negative pressure happens (leeward). An example of this can be seen in **Figure 1**.

Buoyancy, also called stack effect, is the air density difference between the outdoor and indoor air bodies caused by differences in the air temperature. It is the phenomenon when warm air "floats" among a colder mass of air. Although buoyancy is generally related to a vertical flowline, the flow could happen also in a horizontal direction. **Figure 2** shows how stack effect works.

As aforementioned, both driving forces have the same origin: temperature differences. In the case of buoyancy, the warm air is displaced toward a mass of colder

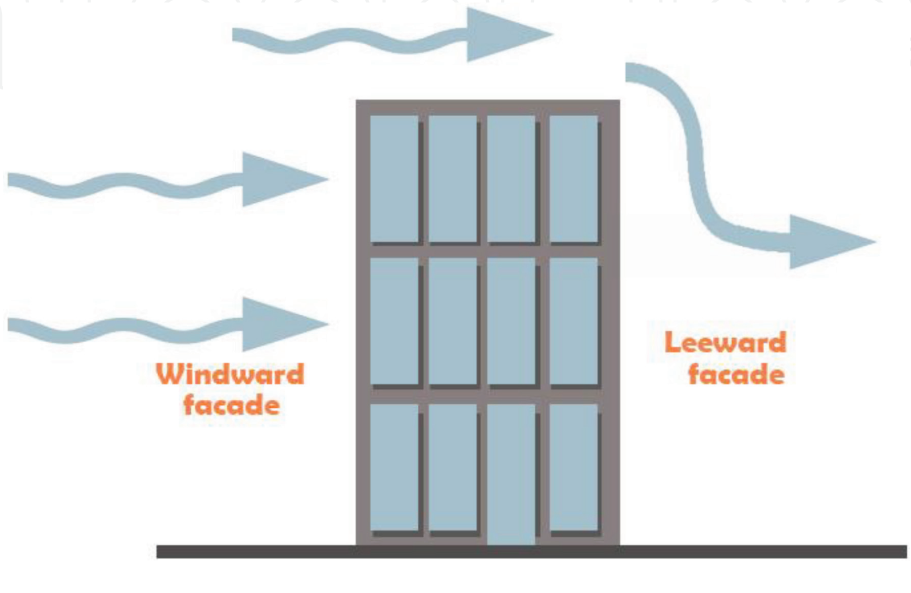

Figure 1.
Natural ventilation due to difference of pressure.

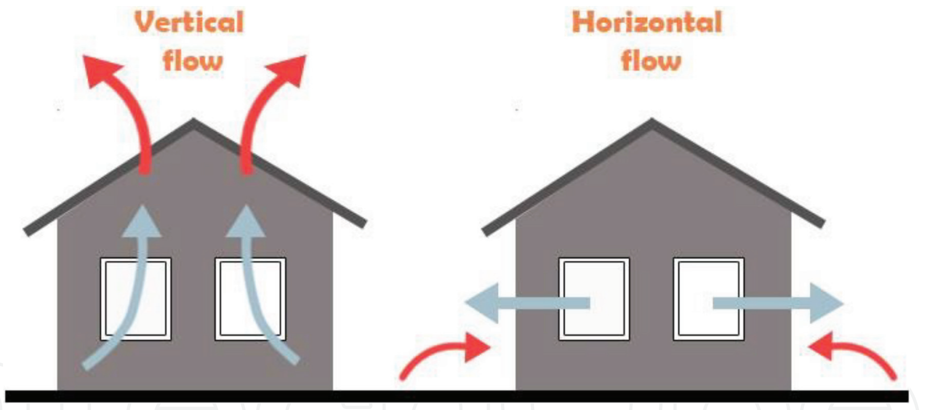

Figure 2.
Natural ventilation due to difference of temperature.

air, either in a vertical or horizontal direction. For wind pressure, the wind flow is headed due to the temperature difference occurred in a large scale. For example, when a mass of air is heated in some region, it floats up; therefore, a mass of cold air tries to cover the empty space that the floated air left. On the path to do this, the air hits the façades of the buildings, hence producing the airflow throughout them.

2.1 Natural ventilation for cooling and IAQ

As it was mentioned, natural ventilation can be used for cooling purposes as well as for achieving levels of IAQ. For the first subject, thermal comfort can be reached by three main manners:

- Cooling the indoor space as long as the outdoor air temperature is lower than the indoor air temperature.
- Refreshing the human body through evapotranspiration (removing the latent heat by the evaporation of the sweat drops of the skin).
- Cooling the building structure and internal heat gains by using convection heat transfer.

For having IAQ, natural ventilation is used by the displacement of the airflow in order to "sweep" the pollutants (positive pressure) or by "vacuuming" and expelling them (negative pressure).

3. Natural ventilation within buildings

Even though wind pressure might help to achieve thermal comfort and buoyancy might improve the IAQ, in this chapter, it is considered that stack effect only helps to reach thermal comfort, and wind pressure only improves the IAQ. This is because the temperature of the airflow is not always suitable to cool down a built space or the human body, in the case of wind pressure, whereas the airflow due to temperature differences is not always strong enough to expel all the pollutants from the indoor space.

3.1 Thermal comfort

The airflow rate by stack effect is calculated as follows [6–8]:

$$V_{stack} = (0.40 + 0.0045 \cdot \Delta T) \cdot A \cdot \sqrt{2 \cdot g \cdot H \cdot \left|\frac{\Delta T}{T_{indoor}}\right|} \quad (1)$$

where V_{stack} is the volumetric airflow due to buoyancy, ΔT is the difference between the outdoor and the indoor temperatures, A is the effective opening area (area of the opening where the airflow actually takes place), g is the gravitational acceleration (9.81 m/s^2), H is the height between the floor and the ceiling, and T_{indoor} is the indoor air temperature.

From Eq. 1 it can be seen that the volumetric airflow by buoyancy depends on the temperature difference, the ceiling height (for vertical airflow), and the effective opening area.

For cooling the space, the temperature difference should be negative; therefore, the indoor heat is expelled. For cooling the human skin, the outdoor temperature must be below 35°C; hence, the convective heat transfer from the human skin to its surroundings is negative (considering the temperature of the skin at approx. 37°C), and then, the latent heat of the skin is removed.

Thereby, if the outdoor conditions are suitable, thermal comfort can be achieved, either by cooling the space or the human skin. In this way, the two other terms of Eq. 1 can be varied in order to reach thermal comfort.

For this, in this document two types of approaches are proposed: building design at early stage and occupant behavior. For the first subject, the height of the ceiling must be correctly stated at the planning stage to optimize the airflow rate. For the second approach, a correct driving of the openings must be applied by the user depending of the indoor and outdoor conditions.

3.2 IAQ

Wind-driven ventilation is proposed to be carried out in order to remove the pollutants originated within the household. These pollutants (dust, odors, smoke, fungus, mist, fur, etc.) have their main origin in the bathroom and kitchen, although it can be generated at other rooms of the dwelling.

The model of volumetric airflow is shown below [6–8]:

$$V_{wind} = \left[0.55 + \left(\left|\frac{\alpha_{effective} - \alpha_{wind}}{180}\right| \cdot 0.25\right)\right] \cdot A \cdot v \quad (2)$$

where V_{wind} is the volumetric airflow due to wind, $\alpha_{effective}$ is the effective angle of the wind (set at 180°), α_{wind} is the actual angle of the wind, A is the effective opening area, and v is the wind speed.

As it can be noticed, Eq. 2 depends on the wind direction and speed as well as the opening area and the orientation of the façade (effective angle of wind). Thereby, the physical characteristics of the wind cannot be modified. Nevertheless, the orientation of the openings has to be analyzed before the dwelling is constructed, whereas the effective opening area could be driven by the occupants in order to adapt the airflow depending of their necessities.

Thereby, from Eqs. (1) and (2), three sets of inputs can be considered as the most influencing factors upon the natural ventilation performance. These sets are shown in **Table 1**.

In this way, the two approaches presented in this chapter are gathered for reaching thermal comfort and IAQ as follows: height of the ceiling and façade orientation as an early building design and a correct driving of the openings as a proper occupant behavior.

	Climate conditions	**Building design**	**Occupant behavior**
Stack effect	Difference of temperature	Ceiling height	Effective opening area
Wind pressure	Wind speed Wind direction	Building orientation	Effective opening area

Table 1.
Main factors for assessing the natural ventilation performance.

4. Natural ventilation proposals and performance

For assessing the performance of natural ventilation within a single dwelling, a model for stack effect ventilation and wind pressure ventilation is determined. A building of 120 m^2 of built area is considered with operable openings that can open from 0 to 3 m^2.

4.1 Thermal comfort

As aforementioned in this book chapter, ventilation by buoyancy is used to achieve thermal comfort within the dwelling, considering that the outdoor temperature is lower than the indoor temperature; therefore, indoor heat is removed. Another manner to reach comfort is the extraction of the indoor heat through a horizontal opening placed on the top of the building (see **Figure 2**).

Furthermore, in this book chapter the volumetric airflow, calculated with Eqs. (1) and (2), is seen as the performance of natural ventilation, either for achieving thermal comfort or for achieving IAQ. Hence, it is considered that the higher is the volumetric flow rate, the more efficient is the natural ventilation method.

Thereby, if an opening is placed in the top part of the building (ceiling/roof), an estimation of the volumetric airflow can be carried out. This architectural arrangement was chosen instead of a horizontal flow because the airflow would be more constant considering that the temperature difference is higher and more often than the occurred in a horizontal plane [5].

For an analysis of natural ventilation by stack effect, two parameters are considered: the ceiling height, which is taken as the building design, and the opening area, which is considered as a factor regarding the occupant behavior. **Figure 3** shows this airflow at different effective opening areas and different ceiling heights.

From **Figure 3** one can calculate that the volumetric airflow increases by approximately 0.12 m^3 per every 0.5 m^2 of the opening area. When the height of the ceiling is higher, the airflow rate increases as well. At the maximum opening area proposed here (3 m^2), there is a difference of almost 1 m^3/s between a height of 2.3 m and another of 2.8 m.

When the airflow is measured by changing the difference of temperature between the outdoor and the indoor air, **Figure 4** can be displayed. In this case, this factor is considered as climate condition, where there is no influence by the occupant behavior nor the building design.

In **Figure 4** it can be seen that the increase rate of airflow is lesser than the rate varying the ceiling height when the opening area enhances. Also, it is noticed that, at an effective opening area of 3 m^2, a temperature difference of 5°C makes a variation of only 0.3 m^3/s.

From **Figures 3** and **4**, it is noticed that the ceiling height, as long as it has an effective opening area, would help to expel the warm air and thus to reach indoor thermal comfort. The temperature difference, although it is an important parameter for the airflow rate, has a lower influence. Moreover, this physical characteristic cannot be controlled at any manner; therefore, its influence highly depends on the randomness of the outdoor and indoor conditions.

To achieve thermal comfort, however, two things must be considered: at an early-stage of construction, the ceiling height has to fulfill a certain value. From **Figure 4** one can establish that this value must be not lower than 2.5 m, if it is considered that from 2.5 to 2.8 m of height, the airflow rate can decrease up to 0.5 m^3/s.

Another approach to take into account is related to the opening driving, where the occupants have a total influence. For this, the openings placed on the ceiling/roof must be easily operable. Also, they have to be designed to protect the indoors from external hazards and conditions such as rain, animals, and burglars.

If these two approaches are correctly carried out, it is highly likely that the indoor temperature decreases. Furthermore, the correct driving of the openings would help to control the temperature if this value is lower or upper the comfort temperature range, set between 18 and 23°C, according to international standards [9].

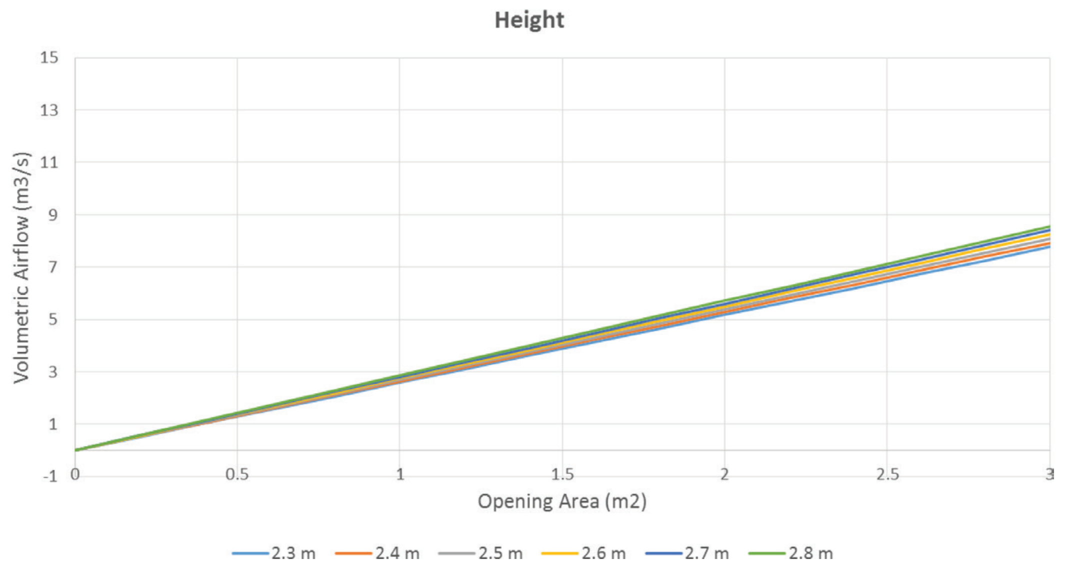

Figure 3.
Volumetric airflow by varying the ceiling height and the effective opening area.

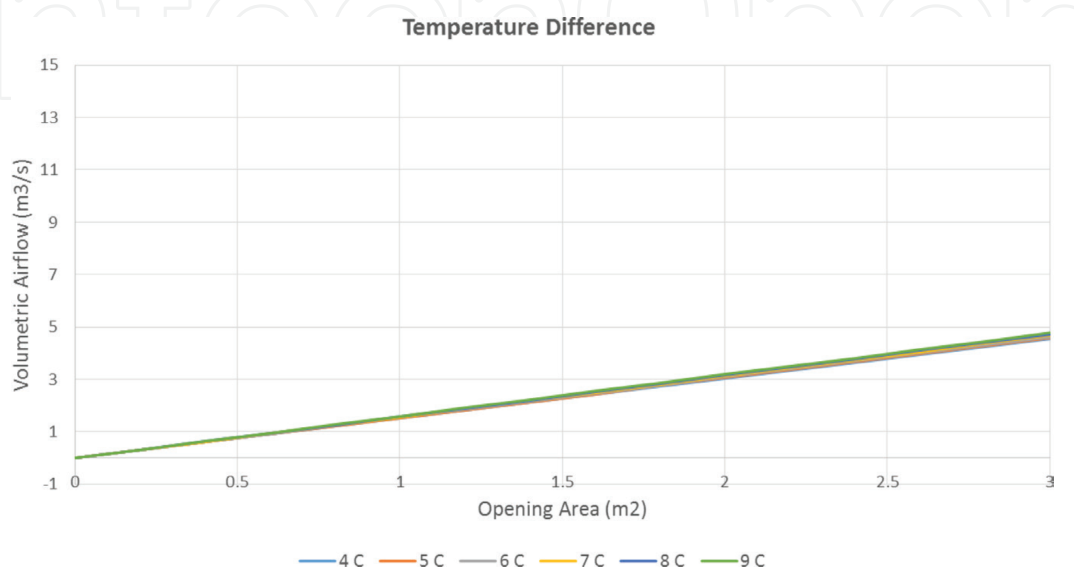

Figure 4.
Volumetric airflow by varying the difference of temperature and the effective opening area.

4.2 IAQ

For achieving correct levels of IAQ, cross ventilation is proposed. This type of ventilation is defined as a horizontal airflow through two openings placed on two façades opposed each other. Thereby, one opening has positive pressure, while the other has a negative pressure, hence increasing the one-direction airflow rate. Results varying the angle of incidence can be seen in **Figure 5**, where this factor totally depends on the building orientation, which is part of the building design.

In **Figure 5** the wind speed was set at 1 m/s, considering this value as sufficient to analyze the airflow rate by varying the angle of incidence. Thereby, it is noticed that the difference between an angle of 15° (almost parallel to the opening) and 90° (perpendicular to the opening) brings an airflow difference of 0.375 m^3/s. This means an airflow rate increases 0.05 m^3/s per every 10°. If the wind speed is higher, this airflow rate increases as well.

When the wind speed is varied, **Figure 6** can be displayed. In this case, the factor to vary, apart from the effective opening area, belongs to the climate conditions, which have no influence by the occupant behavior nor the building design.

In **Figure 6** the angle of incidence was set as perpendicular to the opening (90°). Results show a high airflow rate of increase by increasing the wind speed, having, at an effective opening area of 3 m^2, a difference of 12.15 m^3/s, being this the highest difference rate by varying the different features of ceiling height, temperature difference, angle of incidence, and wind speed.

Furthermore, as with the airflow by buoyancy, the wind speed is an outdoor characteristic that is not possible to control; thus, the airflow by wind pressure is highly dependent on its randomness.

Nonetheless, wind pressure airflow could consider two important features: at an early stage of design, the openings must be placed as most perpendicular as possible to the predominant wind direction of the place. This predominant direction could be taken from climate databases, very common nowadays for almost any place of the earth [10].

And as with stack effect airflow, the opening driving is a very important factor to considerer for controlling the airflow rate. As with the vertical flow by buoyancy, the horizontal airflow by wind pressure can be easily controlled by operable openings (vents, windows, doors) as long as the wind speed is sufficient to propel the airflow rate.

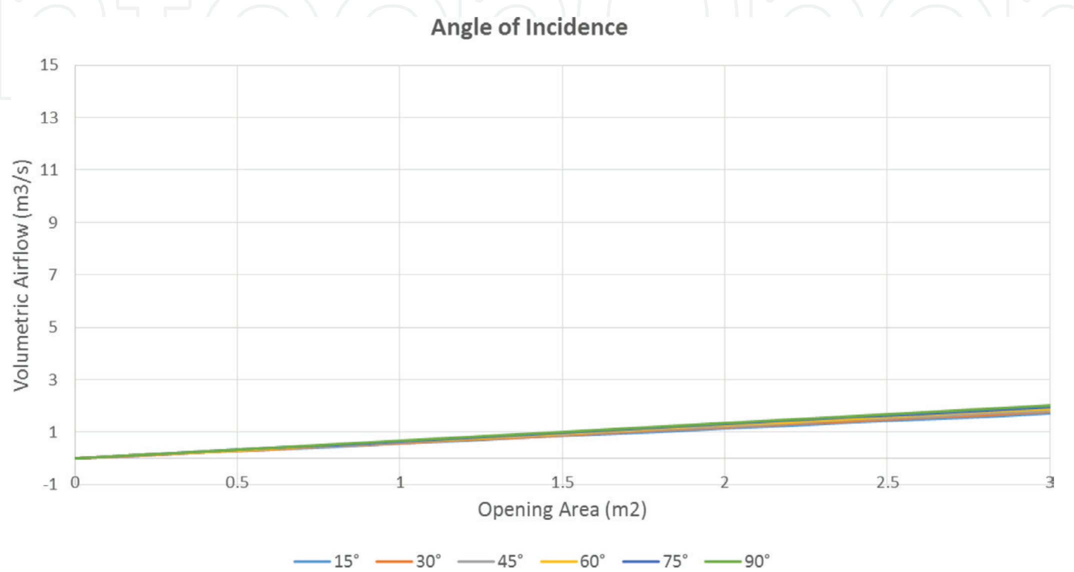

Figure 5.
Volumetric airflow by varying the angle of incidence and the effective opening area.

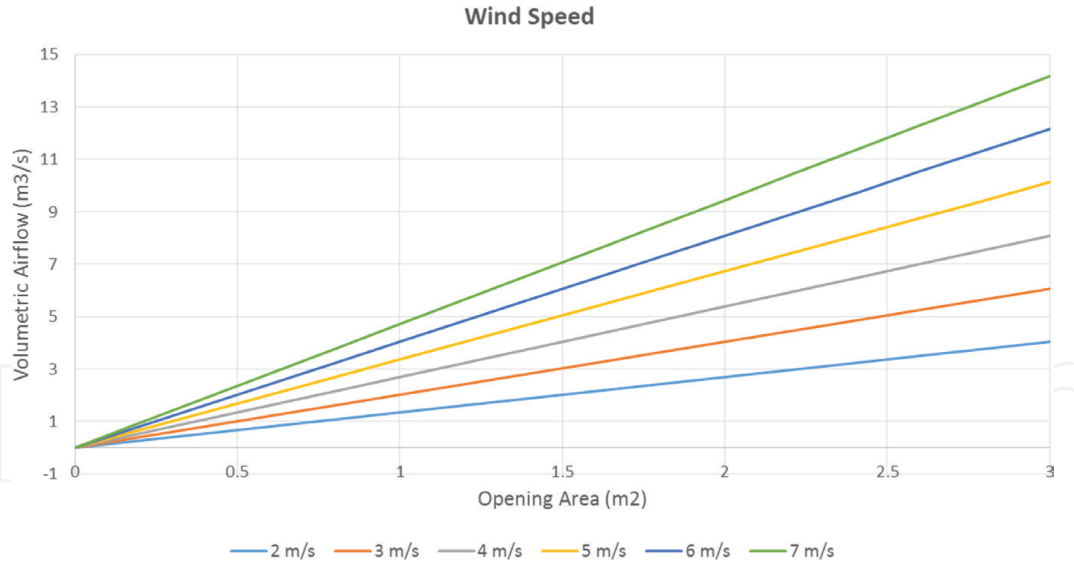

Figure 6.
Volumetric airflow by varying the wind speed and the effective opening area.

4.3 Natural ventilation proposals

With the prior analysis, two proposals are established as fundamental for natural ventilation within dwellings: stack effect for thermal comfort and wind pressure for IAQ. Also, three approaches for the two types of airflow are considered as follows:

- For buoyancy, a minimal ceiling height has to be taken into account. In this chapter 2.5 m is considered as enough.
- For wind pressure, one façade has to be perpendicular to the main wind direction of the place, which has to be calculated based on its local climate data.
- For both, operable openings must be placed. For the case of stack effect, these should be on the ceiling/roof or in the top part of the walls, whereas for wind pressure these should be placed at the façade perpendicular to the predominant wind direction and at its opposed façade.

The two proposals can work alone or together, considering that vertical airflow by stack effect is only efficient for warm conditions, where the temperature difference between the outdoor and the indoor air is high enough to propel the airflow. If the outdoor air temperature is low enough to cool down the indoor space, the only thing that the occupant has to do is opening the window, vent, or door, considering always that this occupant has the total control of the airflow by driving operable openings, either for buoyancy or for wind pressure.

5. Conclusions

In this book chapter, the fundamentals of natural ventilation for dwellings to achieve thermal comfort and indoor air quality are shown. Thereby, it is found that for thermal comfort, airflow by stack effect can be used, while for IAQ, wind pressure airflow could be applied.

In both cases, outdoor conditions, i.e., temperature difference between indoor and outdoor air and wind speed, are features that have high influence on the airflow rates. Nevertheless, these characteristics cannot be controlled by the building occupants; therefore, other approaches are considered.

These approaches are mainly three: the ceiling height, the orientation of the façades, and the driving of the openings. A comparison between **Figures 3** and **6** clearly shows the influence of these approaches upon the natural ventilation performance, where the ceiling height is the second most influencing parameter, followed by the building orientation. In both cases, the effective opening area plays a fundamental role to both increase the volumetric airflow rate and control it when it is necessary.

Nevertheless, in order to optimize the natural ventilation performance, various considerations must be taken. For the two first approaches, a correct design must be carried out before the construction of the dwellings, whereas for the correct driving, not only a proper design has to be done (operable openings), but the correct handling of the occupants is highly necessary.

If these approaches are correctly carried on, it is highly likely to achieve both IAQ and thermal comfort without spending any kind of resource, hence helping to the welfare of the occupants while countering the climate change.

Acknowledgements

The author wants to thank Dr. Astrid H. Petzold-Rodriguez for her useful comments regarding the clearness of the manuscript.

Conflict of interest

The author certifies that he has no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria, educational grants, participation in speakers' bureaus, membership, employment, consultancies, stock ownership, or other equity interests and expert testimony or patent-licensing arrangements) or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this book chapter.

Nomenclature

$\alpha_{\text{effective}}$	effective angle of the wind entrance [°]
α_{wind}	wind direction [°]
ΔT	temperature difference between indoor and outdoor air [K]
A	opening area [m^2]
g	gravitational acceleration [m/s^2]
H	ceiling height [m]
T_{indoor}	indoor air temperature [K]
V_{stack}	volume flow rate due to stack effect [m^3/s]
V_{wind}	volume flow rate driven by wind [m^3/s]

Author details

Ivan Oropeza-Perez
Department of Architecture, Universidad de las Americas Puebla, Mexico

*Address all correspondence to: ivan.oropeza@udlap.mx

References

[1] International Energy Agency [Internet]. 2013. Available from: http://www.iea.org [Accessed: 2018-12-20]

[2] IPCC Working Group III. Special Report of Emission Scenarios [Internet]. 2000. Available from: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html [Accessed: 2018-11-20]

[3] Ekwall T. Residential air conditioning in developing countries. Energy and Buildings. 1991;**17**(3):213-220. DOI: 10.1016/0378-7788(91)90108-F

[4] Ghaffarianhoseini A, AlWaer H, Omrany H, Ghaffarianhoseini A, Alalouch C, Clements-Croome D, et al. Sick building syndrome: Are we doing enough? Architectural Science Review. 2018;**61**(3):99-121. DOI: 10.1080/00038628.2018.1461060

[5] Etheridge D. Natural Ventilation of Buildings: Theory, Measurement and Design. 1st ed. John Wiley & Sons Ltd.; 2012

[6] ASHRAE Handbook of Fundamentals. New York, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc; 2001. Chapter 26

[7] ASHRAE Handbook of Fundamentals. New York, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2005. Chapter 27

[8] ASHRAE Handbook of Fundamentals. New York, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2009. Chapter 16

[9] Oropeza-Perez I, Petzold-Rodriguez AH, Bonilla-Lopez C. Adaptive thermal comfort in the main Mexican climate conditions with and without passive cooling. Energy and Buildings. 2017;**145**:251-258. DOI: 10.1016/j.enbuild.2017.04.031

[10] Han Q, Hao Z, Hu T, Chu F. Non-parametric models for joint probabilistic distributions of wind speed and direction data. Renewable Energy. 2018;**126**:1032-1042. DOI: 10.1016/j.renene.2018.04.026