Ventilative cooling design for a large office building

GUILHERME CARRILHO DA GRAÇA
Instituto Dom Luiz
Faculty of Sciences of the University of Lisbon
gcg@fc.ul.pt

DANIEL P. ALBUQUERQUE
Instituto Dom Luiz
Faculty of Sciences of the University of Lisbon
dpalbuquerque@fc.ul.pt

MARIA M. LERER
Natural Works Consultants
Lisbon
mml@natural-works.com

In the last two decades, the use of natural ventilation in office buildings has been slowly increasing. The best contemporary designs combine natural ventilation with conventional mechanical cooling. When properly designed and implemented these hybrid approaches maximize natural ventilative cooling potential while avoiding overheating during the warmer months.

Keywords: natural ventilation, hybrid ventilation, computational fluid dynamics (CFD), thermal simulation, EnergyPlus.

Introduction

In the mild to warm climate of southern Europe office buildings without operable windows require mechanical cooling during most of the year. This need is the direct result of poorly designed facades that allow for excessive solar heat gains, combined with high internal gains and low exposed thermal mass. These characteristics lead to excessive cooling energy demand in a context of increased public awareness of the environmental and operational costs of building energy consumption. As a result, most current building thermal codes limit the predicted annual energy demand for heating, ventilation and air conditioning systems (HVAC). In the building design phase these predictions result from thermal simulation models with variable levels of detail and approximations. The most complex buildings require models with several thermal zones and, in some cases, tri-dimensional computational fluid dynamics simulations (CFD). In addition to the verification of code compliance, thermal and airflow simulations are used to predict the performance of complex building systems. In tall office buildings natural ventilation is complex system due to the need to compensate for wind velocity increase with height. Many recent designs use a hybrid approach that combines natural ventilation with traditional HVAC solutions. If properly implemented this combined approach maximizes energy savings while avoiding overheating during the warmer months and cold draft complaints in the colder days.

The next pages describe the role of thermal and airflow simulation in the design process of a recently completed hybrid cooling system of an office tower in Lisbon (Portugal), using natural ventilation in combination with a traditional overhead HVAC system. **Figure 1** shows the proposed seventeen-story building (total floor area of 23 000 m²) that includes a small public park in the ground level. The surrounding area is composed by high-density mid to high-rise buildings.

Regulatory framework

As in all EU member states, the Portuguese building thermal and energy consumption code stems from the current version of the EPBD (2010). The code promotes the use of natural ventilation in low-rise buildings by allowing for prescriptive compliance based on minimum ventilation opening areas in each room (5% of floor area). For buildings with more than four stories the code requires performance based compli-

Figure 1. Rendered views of the building (Northwest, South and interior).

ance, typically demonstrated using dynamic thermal simulation or wind tunnel studies. High rise buildings with hybrid cooling and ventilation systems must achieve the following performance standards:

- The building must be able to operate in natural ventilation mode for 70% of the occupied time in a typical year (natural ventilation with no mechanical cooling or heating).
- During the natural ventilation period the maximum CO_2 level cannot exceed 1 250 ppm in more than 10% of the days (each day is evaluated using an 8 h daytime average CO_2 level).

The building energy rating is obtained by dividing the predicted annual energy consumption by the predicted consumption for a building with the same form but standard façade and building systems (no natural ventilation, external shading, no daylight responsive systems), an approach that follows ASHRAE 90.1. In this rating, buildings with hybrid cooling and ventilation have the advantage of using extended space temperature set points in the simulation: 19–27°C, compared to 20–25°C for the reference building and buildings with mechanical ventilation.

Thermal and airflow simulation

The building has a complex corrugated skin that creates two perpendicular distinct orientations in each façade. This geometry brings particular design challenges:

- For each main façade orientation, defining which of the two orientations should be opaque or glazed.
- Defining the required shading systems for orientations with high solar incidence that needed to be glazed (due to valuable views towards the river).
- Assessing the increase in pedestrian level wind velocity in the ground level public park.

In addition to façade optimization the use of a hybrid cooling system created additional design challenges:

- Selecting the most adequate natural ventilation strategy (single sided or cross-ventilation).
- Positioning and sizing the ventilation openings.
- Predicting the natural ventilation system performance.
- Predicting the energy saving potential.

To analyse this diverse set of questions we used three interconnected simulation tools: Ecotect, thermal simulation (EnergyPlus) and computational fluid dynamics (CFD, PHOENICS). The dynamic thermal simulation (EnergyPlus) incorporates results from the other tools: the facade geometry was optimised using *Ecotect* and the wind driven airflow velocities that drive the single-sided natural ventilation system were predicted by CFD (**Figure 2**). These CFD simulations were also used to assess the effects of the obstruction created by the new building on the ground level wind velocity.

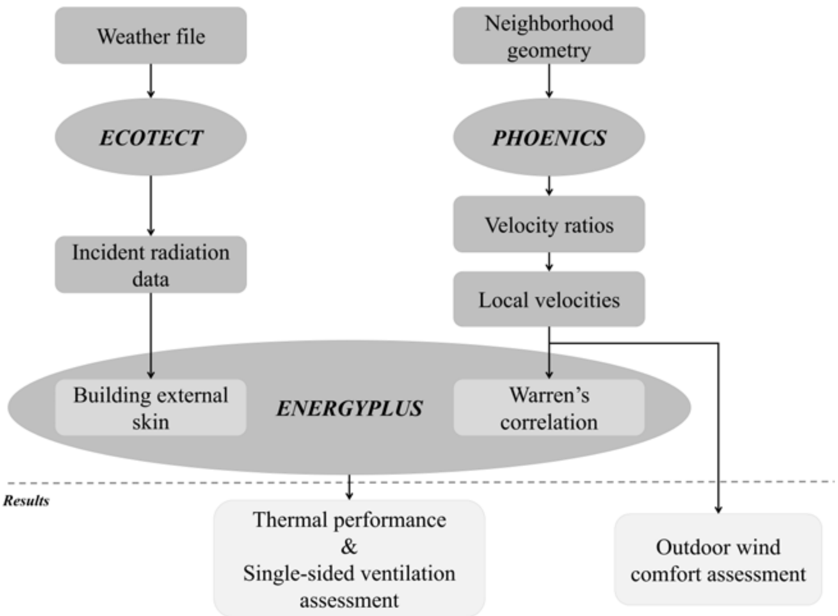

Figure 2. Interrelated simulation tools used in this study.

Pedestrian wind comfort criteria

The construction of a high-rise building in an urban area that was previously vacant always results in narrower pedestrian level wind flow paths that normally increases the maximum wind speeds that pedestrians are subjected to. Since there is no Portuguese standard to assess these problems this study uses the Dutch standard NEN-8100 to evaluate this problem (Willemsen et al., 2007). This standard defines three qualitative classes of comfort (good, moderate and poor) whose wind speed limits depend on the expected outdoor activity (traversing, strolling or sitting). The analysis was based on CFD simulation and focused on six locations in the adjacent plaza.

Optimization of building skin

The base optimization of building skin used the 3D analysis tool *Ecotect* to predict annual cumulative solar incidence for the two perpendicular orientations that exist in each façade. In each façade, the orientation with more than 300 kWh/m² of incident solar radiation was selected to be opaque. The result of this analysis is shown in **Figure 3** (the grey bars indicate the closed portions of the façade). In the southern facing facades, the cumulative solar incidence is high in both orientations. In these cases, the orientation with the worst view was opaque and an external shading system was proposed for the orientation with the best view (the effect of the shading system is shown in red in **Figure 3**).

Natural ventilation strategy and airflow simulation

The use of cross-ventilation in high-rise buildings can be problematic because the large pressure differences that develop across different facades easily lead to excessive internal air velocities. In this building, the geometry and expected internal layout with many single offices steered natural ventilation strategy into a single-sided geometry (SS). The wind driven component of the SS ventilation was modelled using the simple expression proposed by Warren in 1985:

$$Q_w = 0.1 \cdot A \cdot U_L \qquad (1)$$

Where U_L is the velocity parallel to the façade. For a given incoming wind speed and direction this velocity depends on the building and surrounding geometry. The ratio between the undisturbed wind velocity (available in the local weather data file) and U_L was calculated in a set of CFD simulations. Equation 1 was implemented in EnergyPlus that was used to predict the building thermal and natural ventilation performance and size the conventional HVAC system.

CFD simulation

The CFD simulations used the commercial software package of PHOENICS, to predict airflow around and near the building facade for eight wind directions (cardinal and intercardinal). The geometries for each alternative wind direction were obtained by rotating the

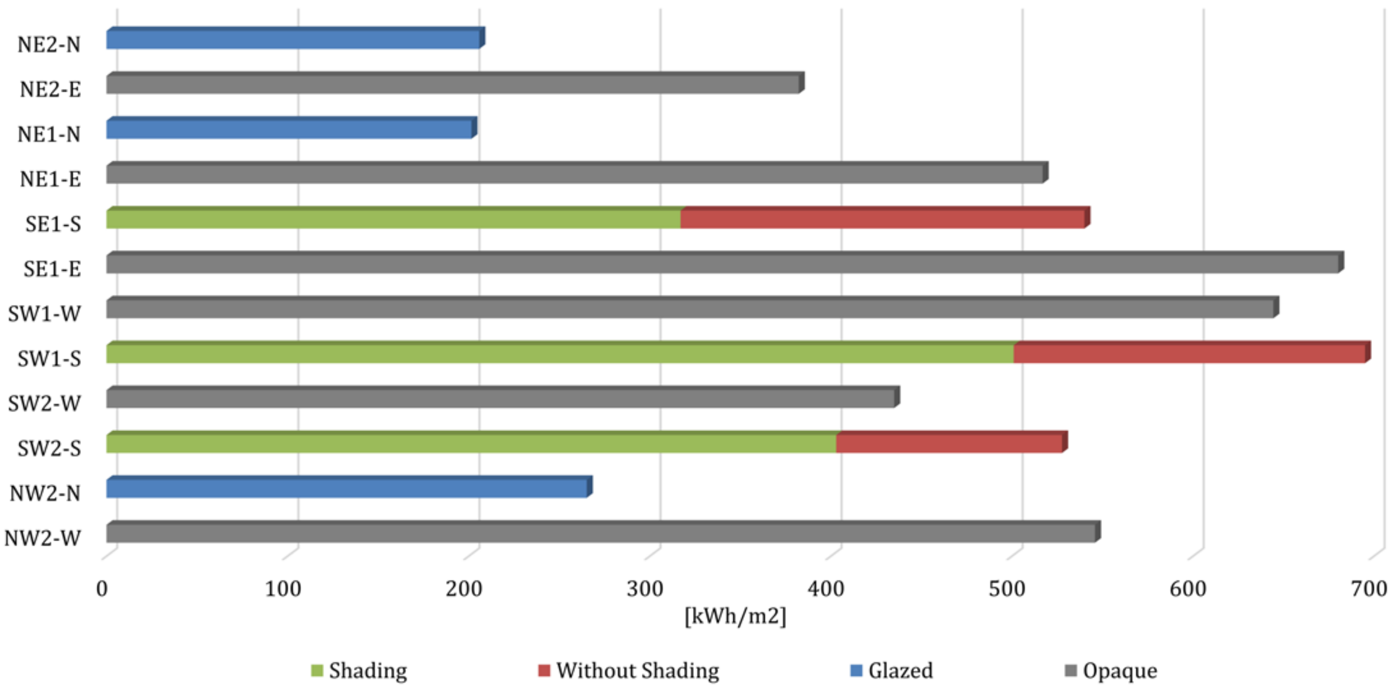

Figure 3. Predicted incident solar radiation for the twelve orientations in the façade.

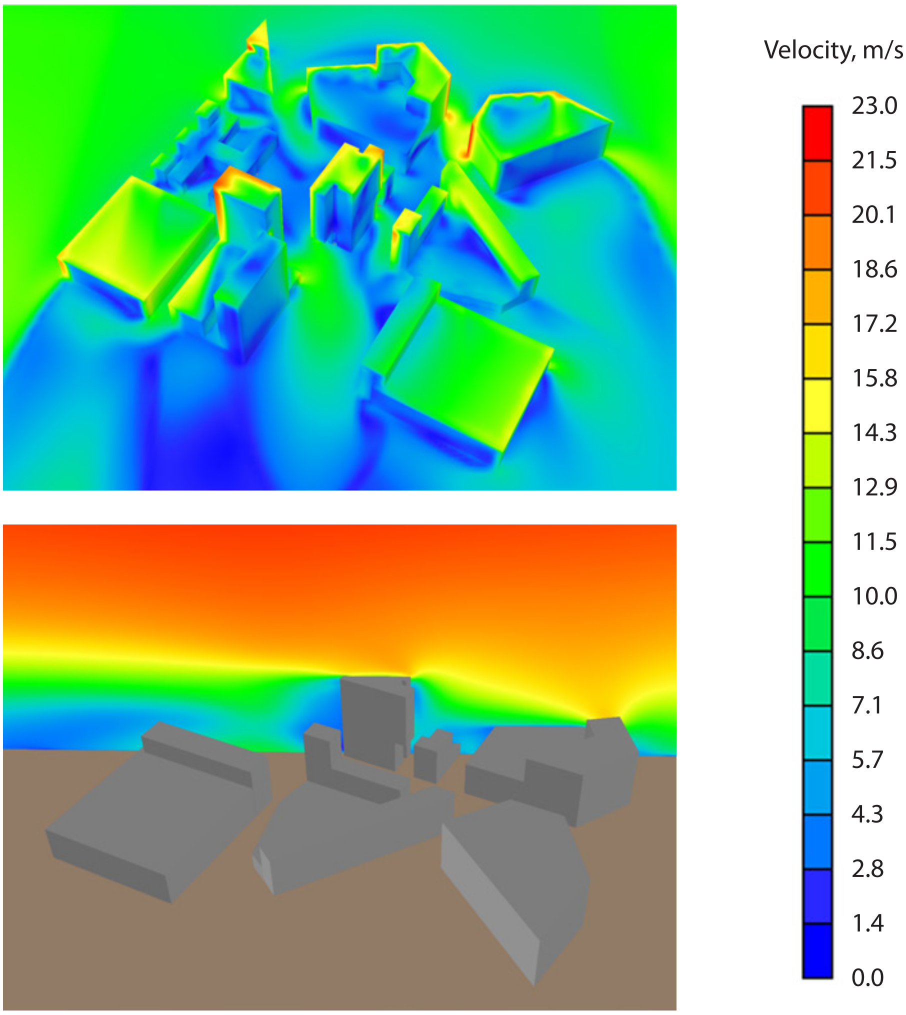

Figure 4. Predicted wind velocities for North incoming wind direction (Top and East views).

neighbourhood/building model inside the simulation domain (45°). The simulations use the k-ε turbulence model, which has been extensively tested for this type of flows (Martins, et al., 2012, Carrilho da Graça et al., 2004, 2012). A logarithmic inflow wind profile was used at the inlet with a wind speed of 10 m/s at a reference height of 10 meters. The bottom of the simulation had a roughness of 0.75 (Blocken et al., 2008). In each simulation the average wind velocities generated near the façades and in the adjacent outdoor spaces were calculated in total of 23 planes. In the façade planes located in three heights (low, mid and high floors) of each main using a control surface spaced 30 cm from the wall and had a height of 4 m by a length of 10 m (spanning two adjacent offices). In the adjacent park, five control surfaces were distributed in North, East, South, West and centre locations.

The pedestrian wind comfort assessment showed that 75% of the adjacent park area achieves an A grade classification (good). Unfortunately, the combination of the new building and an existing tower results in airflow acceleration near the Southern edge of the park where the predicted outdoor comfort index reaches D (moderate comfort for traversing).

Thermal simulation

The dynamic thermal simulations were performed in the open source thermal simulation tool EnergyPlus (average precision of 1.5°C, Mateus et al., 2014). **Table 1** shows the four increasing efficiency simulation scenarios considered in this study.

Table 1. EnergyPlus scenarios description.

Scenario	Description
I	Fully glazed exterior facade
II	I+50% glazed exterior facade
III	II + South shading
IV	III + SS natural ventilation

The forth scenario has bottom hang inward opening windows with a height of 1.5 m and a width of 0.95 m. The simulation used a simplified geometry model of a single floor with periodic boundary conditions (Lerer et al., 2013). The opaque portion of the façades integrates the natural ventilation openings, allowing for the use of an uninterrupted fully glazed section in the transparent orientation. The net opening area of the window is 0.5 m² resulting in an opening to office floor area ratio of 3.8% (below the minimum prescriptive compliance opening area of 4%). The internal set point temperature for scenarios I to III was 20°C – 25°C. As discussed above, scenario IV used an extended range of 19°C – 27°C (as allowed for hybrid buildings). **Figure 5** shows the predicted HVAC energy consumption for each scenario. The overall building optimization process results in a 60% reduction in HVAC energy consumption (total variation between scenario I and IV). The natural ventilation system is responsible for half of this reduction (30% of the HVAC energy consumption). In order to insure 100% thermal comfort hours a mechanical cooling and ventilation system is needed for 24% of the occupied hours. EnergyPlus was also used to simulate and demonstrate compliance with the regulations. The indoor CO_2 levels simulation results indicate that, as expected for a narrow plan building, the natural ventilation system can maintain indoor air quality for 100% of the annual occupied hours.

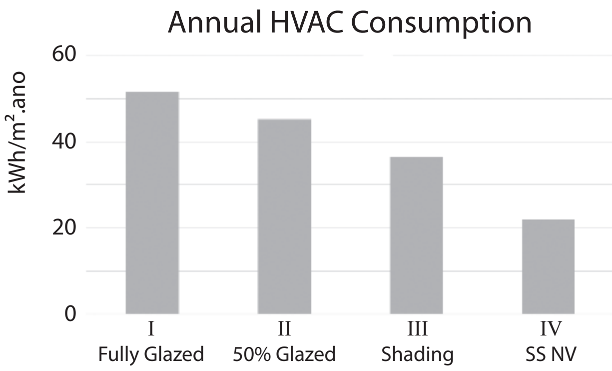

Figure 5. HVAC consumption for an averaged floor.

Conclusion

In most European climates, natural ventilation offers the most potential for reducing CO_2 emissions associated with cooling of office buildings. In spite of the present and other existing examples of natural ventilation use, its potential lies largely untapped. In the present case, this reduction is 30%, approximately half of the total reduction obtained in this optimization study. The combined simulation approach used in the design was able to reduce the uncertainties that are usually associated with natural ventilation systems. ■

References

1. Blocken B., Carmeliet J., 2008. Pedestrian wind conditions at outdoor platforms in a high-rise apartment building: generic sub-configuration validation, wind comfort assessment and uncertainty issues. Wind and Structures 11(1): 51-70.
2. Carrilho da Graça, G., Linden, P. F., & Haves, P., 2004. Design and testing of a control strategy for a large, naturally ventilated office building. Building Services Engineering Research and Technology, 25(3), 223-239.
3. Carrilho da Graça G., Martins N.R., Horta C.S., 2012. Thermal and airflow simulation of a naturally ventilated shopping mall, Energy and Buildings, Volume 50, July 2012, Pages 177-188, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2012.03.037.
4. Malato Lerer, M., Carrilho da Graça, G., Linden, P.F., 2013. Building energy demand response simulation for an office tower in New York, Proceedings of BS2013, 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28.
5. Martins N. R., Carrilho da Graça G., Validation of numerical simulation tools for wind-driven natural ventilation design, Building Simulation an International Journal, Springer, 2015, http://dx.doi.org/10.1007/s12273-015-0251-6.
6. Mateus N.M., Carrilho da Graça G., Pinto A., 2014. Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell, Energy and Buildings, Volume 75, June 2014, Pages 511-522, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2014.02.043.
7. Portuguese Legislation, 2013. RECS – Building Energy Performance Requirements, Portugal.
8. Warren P.R., Parkins L.M., 1985. "Single-sided ventilation through open windows". In conf. Proceedings, Thermal performance of the exterior envelopes of buildings, Florida, ASHRAE SP 49, pp. 209-228.
9. Willemsen E., Wisse J.A. 2007. Design for wind comfort in The Netherlands: Procedures, criteria and open research issues, Journal of Wind Engineering and Industrial Aerodynamics, Volume 95, Issues 9–11, October 2007, Pages 1541-1550, ISSN 0167-6105, http://dx.doi.org/10.1016/j.jweia.2007.02.006.