

## **COOLVENT: A MULTIZONE AIRFLOW AND THERMAL ANALYSIS SIMULATOR FOR NATURAL VENTILATION IN BUILDINGS**

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### ABSTRACT

Understanding the effects of natural ventilation on the comfort levels of a building, during the early stages of its design, can have a considerable positive impact on its final energy consumption. CoolVent is a user-friendly natural ventilation simulation tool that allows visualizing such effects, requiring only the building's bulk characteristics. Unlike similar programs, it couples multi-zone airflow and thermal analysis to predict zone temperatures and airflow rates. This paper provides an introduction to CoolVent's interface, its physical model, and typical results. It is expected that the use of simple tools like CoolVent will promote a wider and smarter use of natural ventilation in buildings.

### INTRODUCTION

The use of natural ventilation has become increasingly popular in the sustainable building design community. If well implemented, it results in great energy savings, while maintaining the indoor thermal and air quality conditions within the desired comfort levels. Furthermore, some studies indirectly suggest that the use of natural ventilation may also be a factor of increased productivity in the workspace (Loftness 2004).

Natural ventilation consists on driving air through a space by taking advantage of the pressure differences caused by a) wind, b) buoyancy forces due to internal temperature differences, or c) a combination of both. Ideally, a natural ventilation strategy should be defined from the early first stages of a building's design, when aspects such as dimensions or construction materials of a building are still flexible.

Unfortunately, there is a lack of simple natural ventilation simulation tools to assist architects during this design phase. The current options include Computational Fluid Dynamics (CFD) tools, and airflow modeling programs. The use of CFD software, like PHOENICS, requires not only an advanced

understanding of the boundary conditions, but also a great amount of details regarding the geometry of the building –parameters which are usually not known while conceiving the design of a building. Moreover, modeling an entire building with CFD is extremely time-consuming. On the other hand, airflow modeling tools such as CONTAM, although relatively simpler to use than CFD, do not account for heat gains or losses. They therefore do not provide any information regarding the variation of the internal building temperature with airflow; they require an input temperature, which is assumed to be constant throughout the simulation. The dependence of the indoor temperature on the air flow rate is an essential piece of information when assessing the comfort levels of a building.

CoolVent is a simple, user-friendly and robust tool that couples airflow and thermal analysis to estimate the comfort conditions inside a naturally-ventilated building. The program was first developed by Tan (2005), and further expanded by Yuan (2007). This document summarizes their work and the later improvements made to the simulation.

### USER INTERFACE

The interface of CoolVent was designed to be simple. In a two-step process, the user can define the input parameters: those characteristics of the building that will mostly influence the effects of natural ventilation, without requiring more detail than what the early design of a building can provide.

The simulation requires less than a minute to run. Results are presented in a format that enables one to clearly visualize the temperature and airflow in each zone of the building. Although the main output interface is visual (i.e. color-based), the user can also access detailed data for each simulation, and store it as a text file.

### Input parameters: General information

Two sets of data are required to run a CoolVent simulation: general and detailed building information. The general information about the building and its location is entered by the user on the window presented in Figure 1.

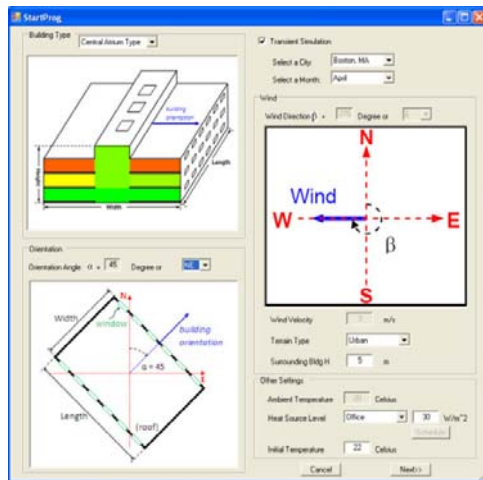


Figure 1 CoolVent interface. Input window for general information of the building (type, orientation, occupancy and weather information, etc.)

**Building type and orientation.** Four pre-defined building types (ventilation strategies) can be modeled: single-sided ventilation, cross ventilation, central atrium ventilation and side atrium ventilation (Figure 2). These geometries represent the most common shapes in newly-built naturally-ventilated buildings. Single-sided ventilation only accounts for the air flow driven by buoyancy forces in a single zone. Cross-ventilation, on the other hand, only addresses the effects of wind. Finally, both central and side atrium designs include a combination of wind- and buoyancy-generated forces. The former involves an occupied zone at each side of the atrium, while the latter has only one occupied zone on the side of the atrium (similar to a solar chimney or wind scoop design).

The user can choose between eight building orientations (N, NE, E, SE, S, SW, W, NW).

**Occupancy heat loads and initial temperature.** The type occupancy determines how much heat is being generated inside the building. In CoolVent, the user can define the occupancy type as residential, office, or educational (predefined heat gains per unit area), or by an arbitrary heat load density, with the option of defining an occupancy schedule. These heat gains represent occupancy, lighting and equipment loads. An initial building temperature must be defined, in order to initialize the calculations.

**Terrain information.** The profile of the wind enveloping the building greatly depends on the terrain information. It is thus important for the user to define the type of terrain (urban, rural, or airport) and the average height of the surrounding buildings.

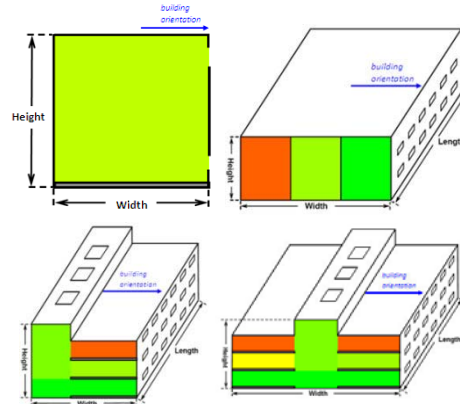


Figure 2 Building geometries (top to bottom, left to right): single-sided ventilation, cross-ventilation, side atrium, and central atrium ventilation.

**Weather conditions.** The simulation can be run for a 24-hour period (*transient case*) or for an instant in time (*steady case*). The transient model uses monthly-averaged typical meteorological year (TMY2) weather data for ten pre-defined cities (Atlanta Boston, Charlotte, Chicago, Houston, Los Angeles, Miami, Puerto Rico, San Francisco and Seattle). The steady simulation requires the user to define the free stream wind speed and its direction (N, NE, E, SE, S, SW, W, NW), and the ambient temperature.

### Input parameters: Detailed building information

Once the general building information has been specified, more precise parameters about the building dimensions must be specified. Figure 3 shows the interface through which the user enters such data.

**Building dimensions.** The building is characterized according to the following parameters: number of floors, occupational floor height, length and width, and roof height and atrium width (for central and side atrium building types only).

**Glazing/opening dimensions.** In CoolVent, the window properties are divided into glazing and opening parameters. Glazing properties determine how much solar heat load is allowed into the building – independently of whether the windows are open or not—, while opening properties directly affect the air flow rate in or out of the building. The user must specify first the areas for glazing and window openings, and secondly, depending on the building type, the vertical location of the openings (single-sided

ventilation), roof opening area (central and side atrium type), and internal door area (cross ventilation).

**Thermal mass description.** Users can characterize the thermal mass of the building by defining: slab thickness, surface (expressed as a percentage of the occupational floor area), building material (concrete, brick or steel), a floor type (exposed, carpeted, raised), and a ceiling type (exposed or suspended). Including the effect of thermal mass in the simulation is optional.

**Window control strategies.** For simulations in winter conditions, CoolVent offers the possibility to a) close the windows if the ambient temperature drops below a user-specified temperature; and/or b) close the windows and turn on the heating if the inside temperature of any of the zones drop below a user-specified temperature.

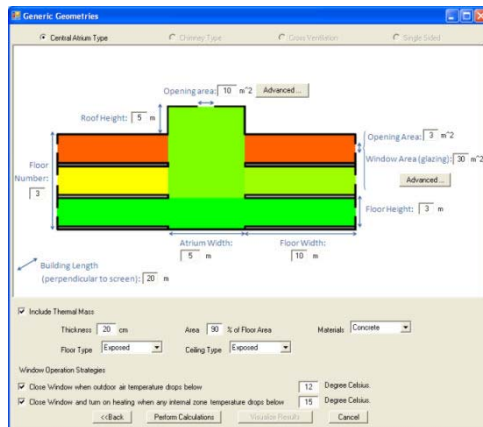


Figure 3 Window used to enter detailed information of the building (dimensions, thermal mass properties, control strategies, etc.).

## Output

The simulation can be run once all the input parameters have been specified. Running the calculations takes less than a minute. Results (zone temperatures and airflows) can be presented in three different formats: as visualization, as data plots, or as a text file.

### Visualization

Figure 4 shows the output of a simulation for the building at a specific instant (screenshot). Each zone of the building is colored according to its temperature, based on a chromatic scale (darkest blue and red for lowest and highest temperatures, respectively). Colored arrows indicate the direction and temperature of the air flow into and out of each zone, and numerical displays provide the magnitude of the airflow rate, in cubic feet per meter (cfm). A list of the temperatures (in °C) for each zone can be found on the lower part of the visualization window. In the near future, a wider availability of output units (e.g., °F, L/s) will be implemented.



Figure 4 Visualization of results: a chromatic scale indicates the temperature of each zone and the air flow; arrows represent the direction of the flow; black rectangles show ventilation rates (cfm).

Transient simulations are visualized as an animation, with an adjustable time interval between each screenshot. Steady simulations are presented as a single screenshot.

### Plots

For transient simulations, it is possible to view in plots the temperature variation of the building over 24 hours. Each plot contains two curves: one representing the temperature variation of a specific zone, and the other showing the change in ambient temperature, over time (Figure 5).

### Output file

Temperature and airflow results can be exported into a text file, separated by zone and time of day.

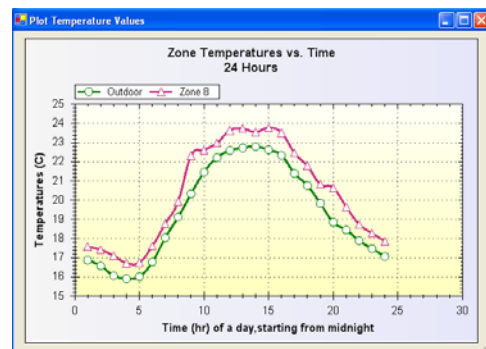


Figure 5 Plots show the variation of a zone's temperature (pink) and the outdoor temperature (green) over a 24-hour simulation.

## MODEL AND CALCULATIONS

CoolVent calculations are based on a multi-zone airflow model. That is, the building is represented as network of multiple zones connected by airflow paths, to which the flow and energy equations can be applied. In each zone, temperature and pressure are assumed to be uniform (i.e., well-mixed zones).

Two equations drive the dynamics of the system: the power-law orifice equation, and energy conservation equation. Both expressions are non-linearly dependent, and must be solved simultaneously in order to obtain accurate airflow and thermal results. The following sections provide an overview of the method implemented in CoolVent to solve the system. A detailed description of the validation for such methods can be found in (Yuan 2007).

### Airflow: Orifice equation

The mass airflow rate  $F_{ij}$  through an opening that connects zones  $i$  and  $j$ , is obtained by:

$$F_{ij} = C_d A \left( \frac{2 \Delta P_{ij}}{\rho} \right)^n \quad (1)$$

where  $\Delta P_{ij}$  represents the pressure drop between  $i$  and  $j$  the zones,  $\rho$  is the density of the air going through the opening,  $A$  and  $C_d$  are the cross sectional area and the discharge coefficient of the opening respectively, and the flow exponent  $n$  is a constant, assumed to be 0.5 for large openings such as doors and windows (Walton and Dols 2006). Following the equation for mass conservation, and assuming no air sinks or sources, the sum of all flows  $F_{ij}$  must be zero.

The discharge coefficient  $C_d$  depends both on the geometrical characteristics of the opening (size, shape, depth, etc.) and on the nature of the flow. For turbulent flow going through a rectangular sharp-edged orifice,  $C_d$  is approximately constant and equal 0.6 (Etheridge and Sandberg 1996).

The pressure drop between the two sides of the opening can be calculated from the Bernoulli equation for steady flow:

$$\Delta P_{ij} = [P_i - \rho_i g(h_0 - h_i)] - [P_j - \rho_j g(h_0 - h_j)] + C_p \frac{\rho v^2}{2} \text{sign}(v) \quad (2)$$

where  $P_x$ ,  $\rho_x$ , and  $h_x$  are the static pressure, density and elevation (relative to the ground) of zone  $x$ , respectively,  $h_0$  is the height of the opening (relative to the ground),  $g$  is the constant of gravity,  $v$  is the ambient free wind velocity, and  $C_p$  is the pressure coefficient of the opening. The sign of  $v$  defines the direction of the flow, and is positive if the air flows from zone  $i$  to zone  $j$ .

The pressure coefficient  $C_p$  depends on several factors, such as wind direction, wall porosity (i.e., opening-to-wall area ratio), ground roughness, height of surrounding buildings, amongst others.

### Heat transfer: Energy conservation equation

Assuming the absence of any air humidification or dehumidification process, the equation of energy for an internal zone  $i$ , connected to one or more zones  $j$ , states:

$$\rho_i c_{p\text{air}} V_i \frac{dT_i}{dt} = \sum F_{ji} c_{p\text{air}} T_j - \sum F_{ij} c_{p\text{air}} T_i + Q_{TMi} + Q_i \quad (3)$$

where  $F_{ji}$  and  $F_{ij}$  are the incoming and outgoing mass flow rates from and into zone  $i$ ,  $T_i$  and  $T_j$  are the temperatures in each zone,  $V_i$  is the volume of air contained in zone  $i$ , and  $c_{p\text{air}}$  is the specific heat capacity of the air. The term  $Q_i$  represents all the heat loads in zone  $i$  that are not related to thermal mass effects. In CoolVent these loads correspond to occupancy (people and appliances/office equipment), solar radiation (direct and diffuse), and heating (only if the corresponding window control strategy was selected –see previous section). The heat gains and losses through the thermal mass are represented by the term  $Q_{TMi}$ .

### Thermal mass

Heat gains and losses in zone  $i$ ,  $Q_{TMi}$ , due to the thermal mass of surfaces  $x$  (walls, ceiling, floor), are calculated by:

$$Q_{TMi} = \sum_x h_x A_x (T_{TM_x} - T_i) \quad (4)$$

where  $h_x$ ,  $A_x$  and  $T_{TM_x}$  are the convective heat transfer coefficient, the surface area and the temperature of thermal mass  $x$ , respectively. For these calculations, one-dimensional transient heat transfer through the thermal mass is assumed. Note that the outdoor temperature (thus the temperature gradient) in transient simulations changes with each iteration, according to the weather data.

The solution for the temperature  $T_{TM_x}$ , is obtained by dividing the thermal mass thickness into a series of “layers”, each of them with a specific thermal resistance, and solving the energy equation, as will be seen in next section.

### Coupling airflow and thermal models: Numerical solution

The non-linear dependence of the air temperature and airflow rate requires the use of numerical methods to obtain a solution to the system. Two methods can be used, both consisting of a series of iterations over different time steps with intervals of  $\Delta t$ . On the first method, called explicit method or “forward Euler”, the term corresponding to step  $t+1$  is only found on the left side of the equation. On the second method (implicit or “backward Euler”), almost all terms, on the left and right side of the equation, refer to the time step  $t+1$ . The first method is straight forward, but lacks stability; the second method requires considerably more computational time (Yuan 2007).

The numerical method implemented in CoolVent (“Cranck-Nicholson” method) uses an average value of both the explicit and the implicit solutions, as shown in equation 5.

$$\rho_i c_{p_{air}} V_i \frac{T_{i,t+1} - T_{i,t}}{\Delta t} = \frac{1}{2} \left( \sum F_{ji} c_{p_{air}} T_{j,t} - \sum F_{ij} c_{p_{air}} T_{i,t} + \sum_x h_{x,i} A_{x,i} (T_{TM_{x,i}} - T_{i,t}) + Q_i \right) + \frac{1}{2} \left( \sum F_{ji} c_{p_{air}} T_{j,t+1} - \sum F_{ij} c_{p_{air}} T_{i,t+1} + \sum_x h_{x,i} A_{x,i} (T_{TM_{x,i}} - T_{i,t+1}) + Q_i \right) \quad (5)$$

In a similar fashion, the term  $T_{TM_{x,i}}$  is obtained by using the Crank-Nicholson method with the energy equation for the thermal mass:

$$\rho_{TM} c_{p_{TM}} \Delta x_i \frac{T_{i,t+1} - T_{i,t}}{dt} = \frac{1}{2} \left( \frac{T_{i-1,t} - T_{i,t}}{R_{i-1/2} + R_{i/2}} - \frac{T_{i,t} - T_{i+1,t}}{R_{i/2} + R_{i+1/2}} \right) + \frac{1}{2} \left( \frac{T_{i-1,t+1} - T_{i,t+1}}{R_{i-1/2} + R_{i/2}} - \frac{T_{i,t+1} - T_{i+1,t+1}}{R_{i/2} + R_{i+1/2}} \right) \quad (6)$$

where  $\rho_{TM}$  and  $c_{p_{TM}}$  are the density and thermal capacity of the thermal mass, and  $\Delta x_i$ ,  $T_i$ ,  $R_i$  are the thickness, temperature and thermal resistance of layer  $i$ . The thermal resistance is convective for the first and last layers, and conductive for all the others.

The boundary conditions are: the temperature of the zones connected by the thermal mass, and a direct heat flow term (assumed to be zero, since in the current version of CoolVent the heat gains from direct solar incidence on the walls are not taken into account).

Results in transient simulations correspond to the last 24 hours of a 96-hour calculation.

### Limitations of the model

Well mixed air assumption. One of the major assumptions of this model is well mixed air in each zone. For most buildings this fact is far from reality: air is usually stratified within a zone. Consequently, buoyancy forces appear even in cross-ventilation designs, and affect the airflow dynamics of the system. For instance, except for single-sided ventilation, the simulation will not show any difference between a building with two vertically-spaced openings of area  $A/2$ , and one with a single opening of area  $A$ . In reality, the first configuration leads to better ventilated zones than the second one.

Open plan assumption. The current simulation assumes a “perfect” open plan configuration: it does not account for any airflow resistance within each zone. This condition is not applicable for closed plan designs, where walls and doors may reduce the airflow rate considerably. Furthermore, if such internal divisions have a large thermal mass, the solution provided by the current simulation may differ greatly from the real case.

Radiative heat sources. The model does not account for radiative heat transfer between the internal zonal surfaces. This assumption may have an important effect on the temperature calculation.

Solar radiation through roof openings Although the current model incorporates the effects of solar radiation through the side windows, it does not account for such

effects through the roof openings. As a consequence, the temperatures in the upper north-facing zones may be underestimated. Furthermore, not including such heat gains prevents the current version of CoolVent from modeling solar towers – a widely-used natural ventilation strategy.

## RESULTS

This section presents four cases of how CoolVent may be used to define the basic dimensions and orientation of a building, so that the indoor conditions remain within comfort standards. The cases are divided into steady and transient simulations.

All the simulations assume an urban terrain type and a surrounding height of buildings of 5m.

### Steady simulations

Steady simulations may be performed when the user wants to understand the basics of natural ventilation (e.g., what is the impact of increasing the area of an opening on temperature/airflow? or that of separating two openings vertically? how does wind affect a specific natural ventilation strategy?) without the need to simulate a 24-hour period.

The results in this section show the impact of vertical separation between single-sided openings, and of wind speed in cross ventilation on indoor conditions. For both cases ambient temperature is set at 20°C.

#### *Single-sided ventilation: Impact of vertical separation between two openings*

A classroom (floor area: 56m<sup>2</sup>, height: 5m, heat load: 40W/m<sup>2</sup>) has two equally-sized openings of 1m<sup>2</sup> each. Both openings are equidistant to the vertical center of the room. Two vertical separations between the openings are analyzed: 1m and 4m.

Figure 6a and Figure 6b show results for the simulations with small and large separation, respectively. Note that to compensate for the assumption of fully mixed zonal air, CoolVent divides single-sided ventilated rooms into two horizontal zones.

The average internal room temperature is 24.6 °C and 23°C and the air flow rate corresponds to 0.30 and 0.48 m<sup>3</sup>/s (637 and 1013 cfm), for the small and large opening separation, respectively. Thus, a larger vertical separation between two openings results in higher airflow rates (consistent with eq. 2) and, consequently, in lower indoor temperatures.

Note that if the area of the opening is relatively small, a large ventilation rate will translate into a high speed of the air jet coming into the room. According to ASHRAE, if such speed exceeds about 1m/s the occupants will feel uncomfortable (and the sheets of paper will begin flying off from desks).

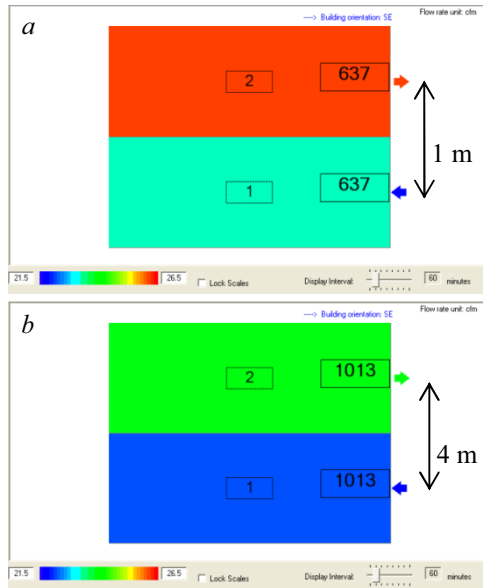


Figure 6 Temperature (°C) and air flow rate (cfm) difference for a) 1m, and b) 4m vertical separations between openings in single-sided ventilation. The bounds of the chromatic scale are 21.5°C (dark blue) and 26.5 °C (bright red).

While obtaining the internal air speed requires modeling the jet – a calculation not implemented into CoolVent yet –, upper and lower bounds can be estimated by calculating the speed of the air at the smallest and largest openings, respectively. In this particular case, with openings of 1m<sup>2</sup>, the air speed through the windows is about 0.3 m/s and 0.5m/s, for the first and second simulations respectively.

In conclusion, while both classroom configurations provide the occupants with comfortable indoor conditions, a larger vertical separation between the openings will guarantee lower temperatures, without exceeding the internal air speed limits.

#### Cross ventilation: Effect of wind speed

A single-floor office building (width: 10m wide, height: 4m, heat load: 30W/m<sup>2</sup>) is divided into four zones of 5m long (each), connected in series (Figure 7). The area of the openings linking each zone internally (doors) is 2.5m<sup>2</sup>, and the total opening area of the windows connecting zones 1 and 4 with the exterior is 2m<sup>2</sup>. Two wind speed conditions are analyzed: 1m/s and 3m/s (Figure 7a and Figure 7b, respectively). The building has an East-West orientation, and the wind blows from West to East.

As results show, the temperature between external and internal temperatures ranges from 21.2°C to 25°C for low wind speed conditions, and from 20.4°C to 21.7°C for high wind speeds. Also, the air flow rate triples from the first case to the second, from 1.0 to 3.0 m<sup>3</sup>/s (2132 to 6414 cfm). The airspeeds at the windows and

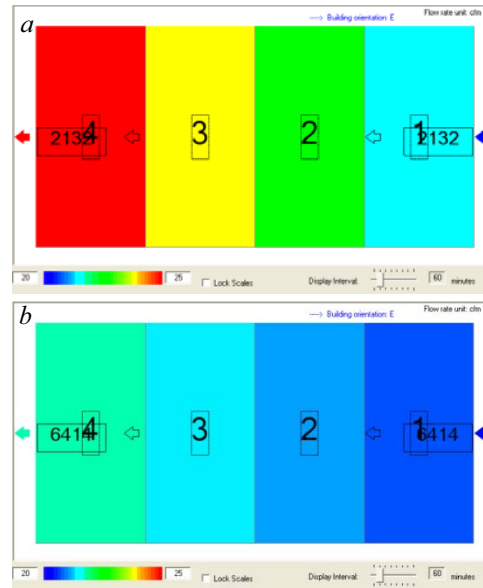


Figure 7 Temperature (°C) and air flow rate (cfm) difference for a) 1m/s, and b) 3m/s stream air speeds in cross ventilation. The bounds of the chromatic scale are 20°C (dark blue) and 25 °C (bright red).

doors rise from 0.5 to 1.5 m/s, and from 0.4 to 1.2 m/s, respectively.

The effect of wind speed is clear: higher wind speeds contribute to higher ventilation rates, and thus to lower indoor temperatures. Once again, however, a wind speed of 3m/s for this particular case results in an internal airspeed that may be excessive close to the window. Several modifications in the building design – aside from the option of partially closing the windows – can help to reducing the internal airspeed and ensuring the occupants' comfort: decreasing the area of the window openings (which would increase the temperature gradient); increasing the area of the window openings (to keep or reduce the temperature gradient); or even changing the building orientation.

#### Transient simulations

These simulations provide an overview of the airflow and thermal dynamics of a building behave over a 24-hour period, given real weather data. In this unsteady case, changing factors such as thermal mass and building orientation have important effects on the indoor conditions of a building. Such effects will be studied in this section.

#### Side atrium configuration: Effect of thermal mass on indoor temperature

A side atrium-type residential has three floors (floor area: 200m<sup>2</sup>, floor height: 3m, occupational heat load: 20W/m<sup>2</sup>). Each floor has window openings of 1.8m<sup>2</sup> and glazing area of 6m<sup>2</sup>. The roof is 3m high (with respect to the top of the third floor), and has openings of 20m<sup>2</sup>. The building has an East-West orientation.

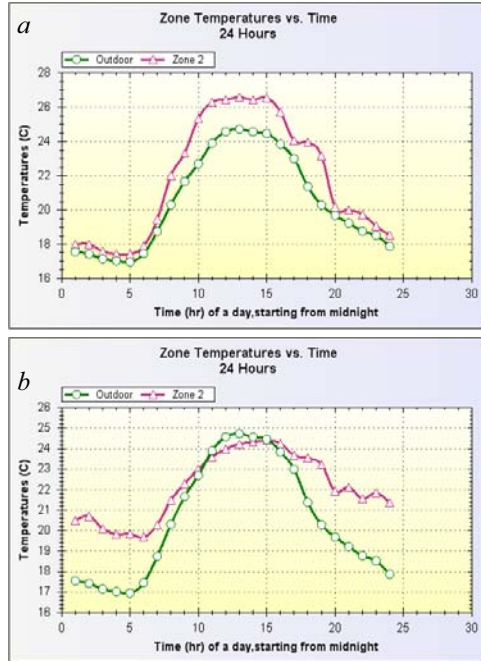


Figure 8 Resulting temperature variations of transient simulations a) without and b) with the inclusion of thermal mass in the analysis. The temperatures of a typical internal zone (pink), and that of the outdoors (green) are plotted over a 24-hour period.

Two cases are studied: one where thermal mass is neglected –an acceptable approximation when construction materials are light– and other considering 20cm-thick concrete slabs, with exposed ceiling and floor.

The weather data for this simulation corresponds to that of the month of April in Houston, TX.

The best way to visualize the effects of thermal mass is through plots. Figure 8a and Figure 8b show the variation of the temperature (triangles) in zone 2 (second floor of the building) for the simulations without and with thermal mass, respectively. Both plots show additionally the variation of ambient temperature (circles).

Note that these results are based on the assumption that windows are open at all times of the day. Any divergence from this assumption may result in a very different output.

*Central atrium geometry: Effect of building orientation on air flow*

The orientation of a building affects how the sun warms the different zones, and how the wind hits each façade. This, in turn, determines whether buoyancy- or wind driven forces dominate the flow dynamics and internal temperatures. As wind conditions vary greatly from one location to another and throughout the year, the resulting flow behavior can be rather unpredictable without a transient simulation. For some

cities, the orientation of a building could be a decisive factor on the kind of natural ventilation strategy to be implemented.

A central atrium-type office building has three floors (floor area: 2x200m<sup>2</sup>, floor height: 3m, occupational heat loads: 30W/m<sup>2</sup>). Each floor has 3m<sup>2</sup> of window openings and 30m<sup>2</sup> of glazing area (50% of the façade) on each side. The roof is 3m high (with respect to the top of the third floor), and has openings of 10m<sup>2</sup>. The thermal mass properties are the same as in the previous section, but only 10 cm thick. The temperature and airflow conditions for two building orientations, North-South (NS) and East-West (EW) are compared, for the same time of day: 12:30 pm.

The simulation is set in Boston, for the month of June. A different flow regime is observed for each case: on a NS orientation (Figure 9a) wind forces dominate over buoyancy, and thus the air flows with cross ventilation. On the other hand, on an EW orientation (Figure 9b) buoyancy forces dominate and the air flows out exclusively through the roof openings. This difference in flow (relatively constant throughout the 24-hour simulation) is due to the fact that in June, Boston winds run predominantly from North to South.

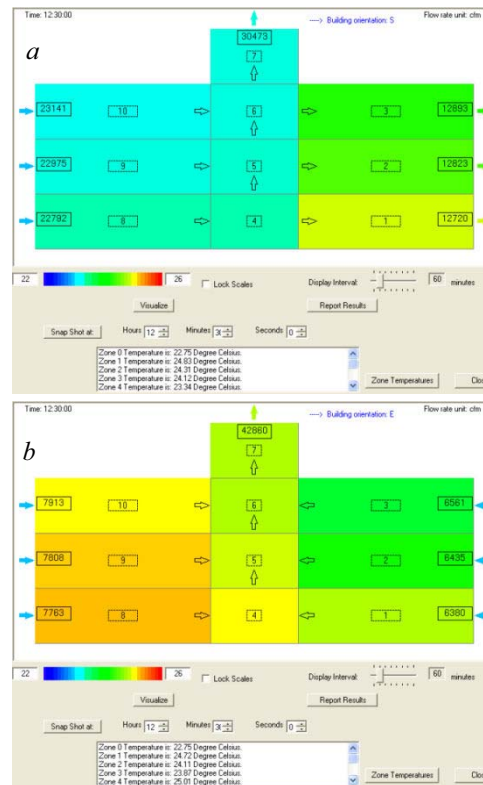


Figure 9 Indoor conditions of a central atrium building, located in Boston, during the month of April (screenshot of 12:30 pm). Two building orientations are simulated: a) North-South, b) East-West. The chromatic scale ranges from 22°C (dark blue) to 26 °C (bright red). Air flow rate (solid rectangles) is expressed in cfm.

During the day, air flow rates through the occupied zones reach up to 13.9 m<sup>3</sup>/s and 7.7 m<sup>3</sup>/s, while the maximum internal temperatures correspond to 25°C and 28 °C, in the NS and EW orientations, respectively. The airspeeds through the openings are closer to the comfort range in the EW building, yet still higher than 1m/s. Smaller openings or a higher thermal mass may contribute to reducing both air speed and temperature.

No cross effects of solar heat gains and building orientation can be appreciated zone by zone in these simulations. This is because of the air flow rate is high enough that the air rapidly mixes inside the building, and homogenizes the air temperature.

### FUTURE WORK

- As mentioned within the current limitations of the simulation, air stratification within zones, closed plan configurations, internal radiative heat transfer, and solar heat loads through roof openings should be incorporated into the model.
- The use of thermal mass for night cooling is an important natural ventilation strategy used for climates where the daytime ambient temperature is higher than the desired comfort temperature inside a building. It is therefore important to consider incorporating this design into CoolVent.
- Usually the openings on the first floor of a building have different properties than those in the other floors (e.g., there may be several doors and no windows on the first floor, and several windows but no doors in the upper floors). Although one of the main features of CoolVent is having a simple interface, it may prove useful to distinguish the lower floor geometrical parameters from the others.
- Given that reducing energy consumption is within the main objectives of the use of natural ventilation, it would be useful to provide the user with information about the energy consumption of the building, with and without the use of natural ventilation.
- Finally, usability tests of the software's interface should be performed, to ensure that the end users (architects) will successfully adopt CoolVent as a modeling tool.

### CONCLUSION

Several factors influence the performance of natural ventilation systems in buildings. CoolVent is a user-friendly tool developed to assist the architect in understanding such influence, during the early stages of a design. (Once the final design has been defined, a full CFD simulation of the building may still be needed, in order to have a detailed model of its indoor airflow and thermal dynamics.)

The program predicts the temperature and ventilation rate through the different zones of a building, using a multi-zone coupled thermal and airflow model. A visualization of the output allows the user to have an easier understanding of the flow and thermal dynamics inside the building. Steady and 24-hour simulations can be performed.

Four case studies presented in this paper show how some parameters of the building's geometry or location affect its internal temperature and air flow. An adequate design of natural ventilation systems can lead to considerable savings in the energy consumption of a building, while maintaining the indoor comfort levels within acceptable limits.

### ACKNOWLEDGMENT

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