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Use of simulation in the design of a large, naturally ventilated office building

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The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. The EnergyPlus thermal simulation program was used to evaluate different ventilation strategies for space cooling and rationalize the design of the façade. The strategies include ventilation driven by different combinations of wind, internal stack and external stack. The simulation results indicate that wind-driven ventilation can maintain adequate comfort even during hot periods. Computational fluid dynamics was used to study the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outside conditions and thereby inform both the design of the windows and the control strategy.

1 Introduction

A new Federal Building for San Francisco is currently under construction. The open-plan office spaces that comprise the majority of the building will be naturally ventilated, with no mechanical ventilation or cooling.[1] The EnergyPlus building energy simulation program,[2] has been used to support the initial design of the building by simulating the performance of a number of different natural ventilation strategies, as described later. The paper also describes the use of computational fluid dynamics (CFD) to study the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outside conditions. The design of the control strategy, and the use of EnergyPlus and CFD in informing and in testing the strategy, are described in a companion paper.[3]

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The part of the building that contains the naturally ventilated spaces is a narrow plan high-rise tower, elongated in the NE–SW direction. Plans and sections of a typical floor are shown in Figures 1 and 2. The width of the building is 19 m and the height of the exposed, high-mass ceiling slab is 3.3 m above the raised access floor. The central third of the floor plan consists of stairwells, elevator shafts, bathrooms and air-conditioned conference rooms. Air can flow from one side of the floor to the other through corridors and above the conference rooms and bathrooms. The SE façade is articulated by a perforated metal scrim external to the glazing, which also serves to reduce the solar gain by ~50%.

2 Climate

The simulations were performed using the TMY2 meteorological data measured at San Francisco International Airport. A comparison of the measured wind regimes at the building site in downtown San Francisco and at the

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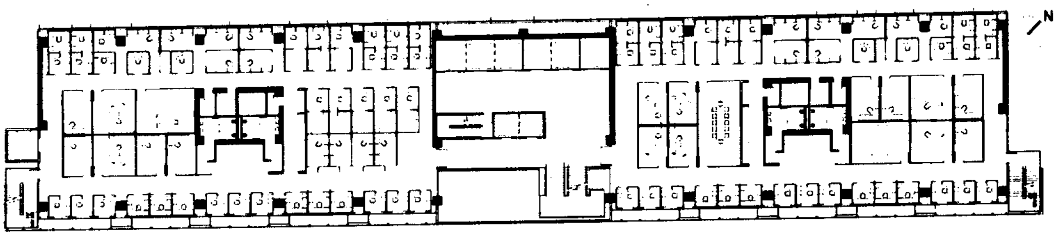

Figure 1 Plan of a typical floor. The building is 122 m long and 19 m wide

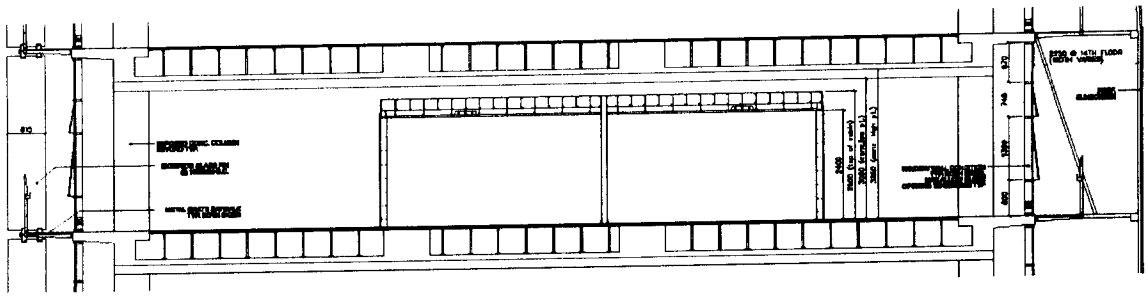

Figure 2 Section of a typical floor of the SFFB. The NW is on the left. The meeting rooms in the centre are conditioned and reach a height of 2.8 m, leaving a gap that allows for the passage of air

airport indicates that the wind speed and direction at the gradient height of the atmospheric boundary layer at each location are not significantly different. It is then only necessary to allow for the effects of the urban terrain, which is done by assuming a wind velocity profile exponent of 0.14. A comparison of the ambient temperature measurements for the two locations indicates

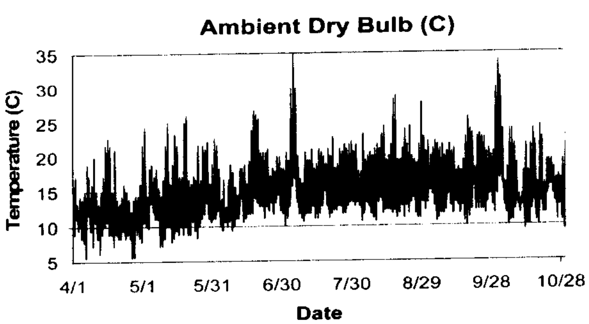

Figure 3 Ambient dry bulb temperature from April to October from the TMY2 for San Francisco airport

that summer daytime temperatures are 2–4K lower at the building site than the airport, while summer night-time temperatures are approximately equal at the two sites. This indicates that using meteorological data measured at the airport is slightly conservative. Issues relating to climate change have not been addressed.

Figure 3 shows the variation of ambient dry bulb temperature during the warmer half of the TMY2 year. On most days, the maximum temperature does not exceed 21°C and only for a few limited periods is it over 27°C. These periods, which typically do not exceed 3 days, are the periods for which there is the most significant risk of overheating.

3 Selection of natural ventilation scheme

Two initial questions facing the design team were:

1) Is there is a need to use buoyancy effects arising from inside–outside temperature differences to supplement the wind?
2) If there is such a need, is the stack-driven flow resulting from the use of high and low openings within the height confines of a single floor sufficient, or are sources of additional buoyancy, such as external chimneys on the SE façade, required to give acceptable thermal performance?

These questions were addressed by using EnergyPlus to simulate different natural ventilation strategies involving different combinations of wind and buoyancy-driven flow.

4 Modeling

EnergyPlus is a whole building energy simulation program that predicts interior thermal conditions by simultaneously solving heat balance equations for the surfaces and room air in each enclosed space. Convective and long wave and short wave radiative transfer are treated separately and explicitly. Daylighting and lighting controls are modeled in order to allow the effects of choice of glazing and window control strategy on artificial lighting use and solar heat gain to be investigated. The COMIS interzone airflow simulation has been integrated into EnergyPlus,[4] allowing ventilation rates, and their thermal consequences, to be recalculated at each time-step. Ventilation rates are calculated by solving a network consisting of nodes connected by flow elements that correspond to openings between spaces and between spaces and the outside. Buoyancy-driven flows are predicted using space temperatures calculated at the previous time-step; there is no iteration between the air-flow and thermal calculations. A time-step of 15 minutes was used in the simulations.
The strategies modeled were:

- *Wind only*—continuous openings along both the NW and SE facades at the same height. Since the openings are at the same height, there is no buoyancy-driven flow.
- *Internal stack*—continuous openings at floor level on the NW façade and at ceiling level on the SE façade, which produces an internal stack; there are no wind effects.
- *Internal and external stack*—continuous openings at floor level on the NW façade, high openings into three storey high chimneys on the SE façade, no wind effects
- *Internal stack + wind*—continuous openings at floor level on the NW façade and at ceiling level on the SE façade. The flow is produced by a combination of wind and internal stack effects.
- *Internal and external stack + wind*—continuous openings at floor level on the NW façade, high openings into three storey high chimneys on the SE façade. The flow is produced by a combination of wind and internal and external stack effects.

A representative 9 m section of one open plan office floor was modeled as a single thermal zone, including the appropriate internal and solar heat gains. The external chimney, when present, was modeled as a second thermal zone, as shown in Figure 4. A discharge coefficient of 0.5 was assumed for each opening (a conservative value that allows for pressure drop through the scrim). Initially, pressure coefficients were estimated from data in Chapter 15 of the ASHRAE Handbook of Fundamentals.[5] Later runs used pressure

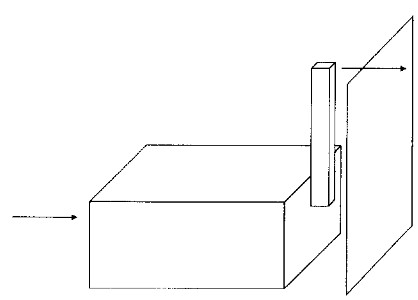

Figure 4 Two zone model of a section of one floor with an external chimney

coefficients measured using a scale model in a wind tunnel; no significant changes in thermal performance resulted from using the experimentally determined coefficients in this case.

A semi-transparent detached shading element is used to model the on-axis transmission of the metal scrim. The off-axis optical properties of the perforated metal scrim were simulated using overhangs and side-fins to produce a rectangular reveal that has approximate geometrical similarity to the circular holes in the scrim. The different ventilation configurations were simulated for the period 1 April to 31 October of the TMY2 composite weather year for San Francisco International Airport. The windows are opened whenever the inside air temperature exceeds both the set-point and the ambient temperature.

4.1 Comfort criteria

The client (the US General Services Administration) accepted the proposal of the design team that the naturally ventilated portions of the building should have comfort criteria based on the adaptive model currently being added to ASHRAE Standard 55,[6] which links the indoor comfort temperature to the mean monthly outdoor air temperature. The upper limit of the 80% acceptable range of indoor operative temperature is 79–82°F for the cooling season (1 April–31 October). The extension to ASHRAE Standard 55 does not account for humidity; however, the maximum value of the ambient dew point in the San Francisco TMY2 is 15°C and the typical daily maximum value in the summer is ~12°C, so humidity does not have a significant influence on comfort if the internal latent gains are small, as they are in offices. The adaptive model assumes that occupants will change their clothing and metabolic rates (within limits) in response to changing conditions in order to maintain comfort.

4.2 Simulation results

Operative temperature, which is an average of the dry bulb and mean radiant temperatures, is used as an indicator of thermal comfort. The performance of the different strategies was evaluated by predicting the number of 'degree hours' above selected base temperatures during occupied hours and the results are shown in Table 1. The case in which the building is completely unventilated is presented for comparison. The main observations are:

1) Wind-driven night ventilation produces reasonable comfort conditions during the day for all but a few days of a typical year.
2) Internal stack-driven night ventilation resulting from low level openings on the NW and high level openings on the SE is less effective than wind-driven ventilation. Analysis of the simulation results shows that the internal temperature on hotter days is 0.5–1K higher than for the wind-driven case (see later).
3) A combination of wind-driven and internal stack-driven ventilation produces a modest improvement in performance compared to the wind-only case.
4) Addition of external chimneys does not improve the performance of the combination of wind-driven and internal stack-driven ventilation, and may be slightly

Table 1 Degree hours above various base temperatures

Base temperature (°C)	Wind only	Internal stack	Int & ext stack	Int stack + wind	Int & ext stack + wind	No ventilation
22.2	160	282	240	155	158	8089
23.9	44	66	57	42	42	4941
25.5	7	14	11	6	7	2380

counter-productive, presumably due to the increased flow resistance caused by the chimney. In the absence of wind, addition of external chimneys helps the internal stack somewhat.

The operative temperature exceeds 25°F on 6 particularly hot days during the typical year, when the maximum ambient air temperatures are in the range 30–35°C. Figure 5 shows the performance of the different strategies on one of these days, 3 July 1970, which was the third day of a sequence of three extreme days. The preceding 2 days had maximum temperatures of 30°C and 35°C. As a result, the building is not significantly pre-cooled at the beginning of the occupancy period. The rise in internal temperature during the first 8 h of occupancy is limited only by the thermal capacity of the building, since the outside temperature is too high for ventilation to be useful.

Figure 6 shows the performance on a more typical warmer day, 16 June 1971 (the eleventh hottest day in the typical year). The building has been significantly pre-cooled overnight, possibly excessively so. The relative performance of the different strategies is essentially the same as that on 3 July, in spite of the night-time ambient temperature being significantly lower, relative to the interior temperatures, which would be expected to give rise to greater buoyancy-driven ventilation rates. It may be noted that, since the building is already slightly overcooled at the beginning of the day, the performance during the afternoon is limited by a combination of the available thermal capacity and the effectiveness of the solar control. This is because the ventilation rate during the day is kept low because the ambient temperature is high.

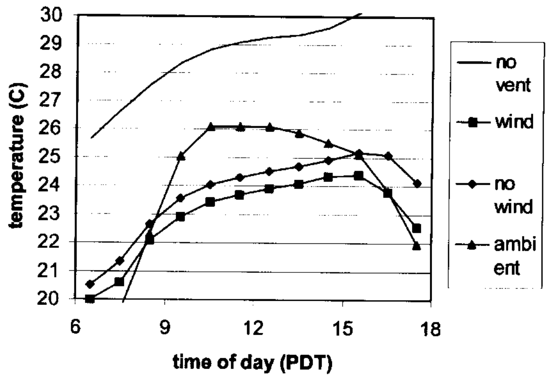

Figure 6 The operative temperature on 16 June for the different ventilation strategies

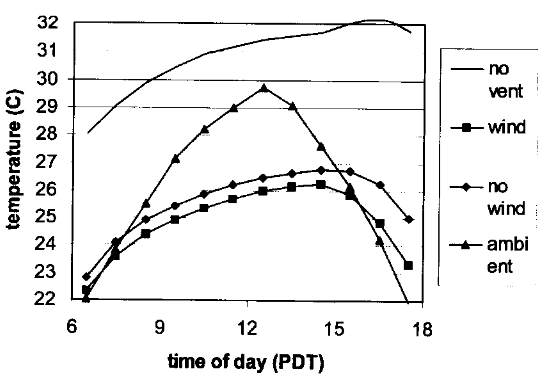

Figure 5 Predicted operative temperature for different ventilation strategies on 3 July. The various strategies that involve wind are indistinguishable from each other and are indicated by 'wind'; the strategies that involve only buoyancy are also indistinguishable and are indicated by 'no wind'. The case of no ventilation is shown for comparison

5 CFD analysis

Detailed analysis of the ventilation performance of a typical naturally ventilated floor allowed for fine tuning of the design. It provided predictions of the cross flow ventilation (CV) airflow pattern, the maximum velocities in the occupied volume of the workspace, and the ventilation efficiency and ventilation flow rates for variable wind conditions. The configuration of the ventilation apertures in the façade and the office furniture design were tuned as a consequence of this study.

The first step in the analysis was to simulate the internal CV flow, using the geometry shown in Figures 2 and 7. The simulated region was one quarter of the naturally

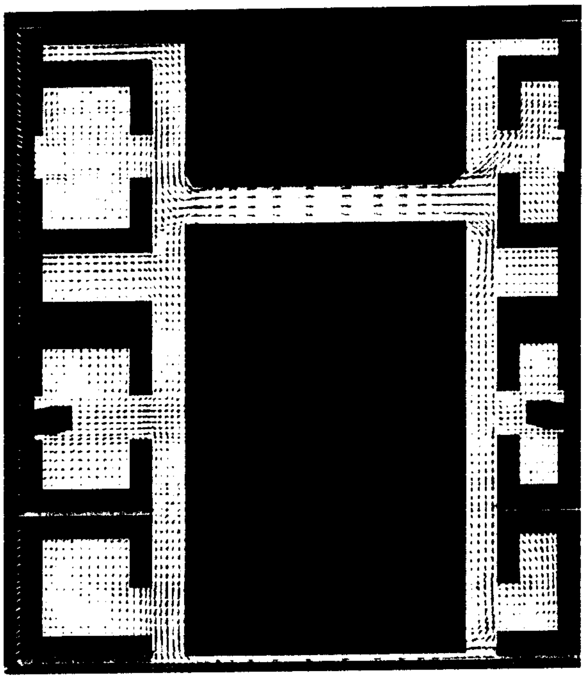

Figure 7 Case 1, bottom view, $z = 1$ m. The NW wing is on the left and the SE wing is on the right. The grey rectangle in the upper center of the figure is the service core and in the middle and lower centre is the meeting room

ventilated portion of a typical floor. This reduced simulation region is possible because of the symmetry and repetition of the floor plan of the building. The simulation domain spans one half of one side (specifically the NE half of the NW side of a typical floor). The two facades have symmetric upper and lower openings, consisting of rows of top-hinged windows (see Figure 2).

Workstation furniture was added to the model, according to specifications provided by the designers, allowing both for a more realistic simulation and for testing of the furniture configuration, in particular the use of porous vertical furniture panels. The ceiling is corrugated concrete with a sinusoidal cross-section. This curved geometrical feature was simulated in an approximate way, using stacked parallel-piped shapes.

The CFD domain included a region around the building in order to reproduce the behaviour of the wind driven airflow as it comes through the windows. The simulations were performed using a commercial CFD package.[7] Simulations were considered converged when the normalized residuals were smaller than 10^{-3} and the solution field was stable: i.e., the values did not change by more than 10^{-7} (relative change) between iterations, and showed no visible fluctuation or changes after hundreds of iterations. The effects of turbulence were modeled using the standard k-ε model. Results of simulations for different flow rates showed a linear variation of the air speeds in the room with inlet speed, as expected.[8]

Table 2 shows the general characteristics of the cases analyzed. The column labeled: %opening used is the open area as a percentage of the total available opening area for each configuration. The result of the simulation using this geometry and a 1m/s external NW wind (perpendicular to the façade) is shown in Figures 7 and 8a, 8b, 8c. The dominant aspect of the predicted flow is the large recirculation zones in the occupied regions of the space. The inflow jet enters from the two windows (lower and upper, see Figures 2 and 8) attaches to the ceiling and exits through the SE bay. This flow pattern is very effective in two respects: ensuring significant cooling of the ceiling slab with night time wind-driven airflow, and avoiding high velocities in the occupied zone during the day.

Table 2 Cases analyzed

Case	Upper opening	Lower opening	Total possible percentage opening used	Furniture panels
1	All open	All open	100	Standard
2	All open	All open	100	Porous
3	All open	All closed	66	Standard
4	Half open	All open	77	Standard
5	Half open	All closed	45	Standard

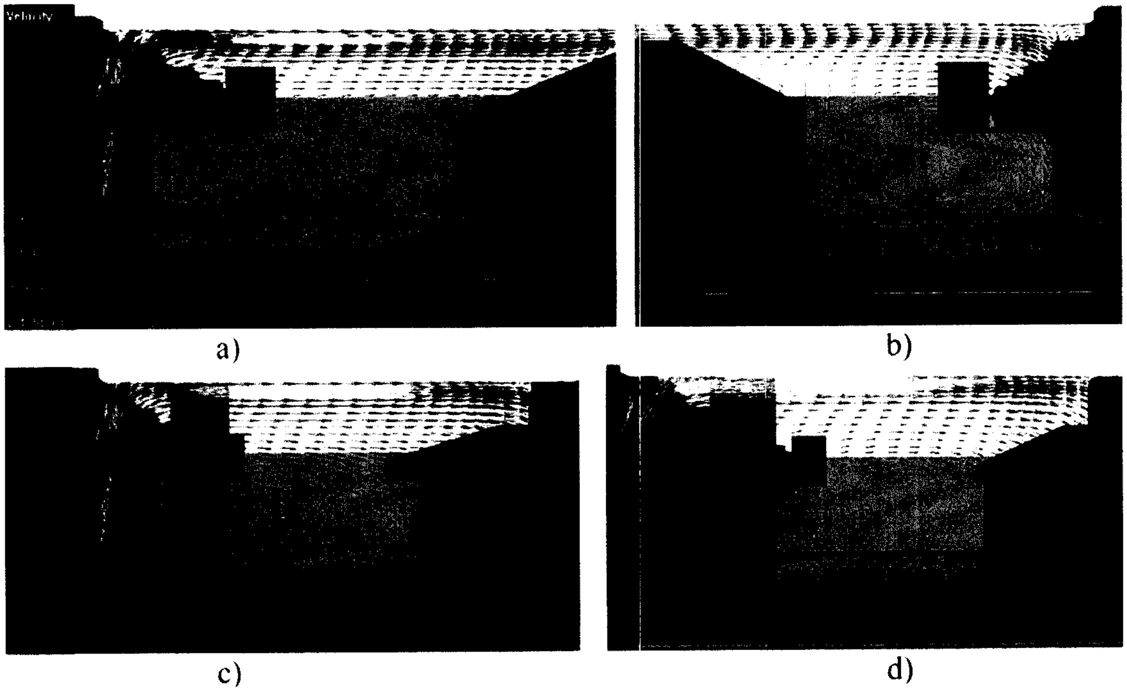

Figure 8 Side view of the velocity field (m/s) in the NW (a), c) and d) and SW (b) wings. a) Flow in the NW bay, in a section spanning over a meeting room, all windows open; b) Flow in the SE bay, in a section spanning over a meeting room, all windows open; c) Flow in the NW bay, in a section obstructed by a service core, all windows open; d) Flow in the SE bay, in a section obstructed by a service core, user operable windows closed. The main effect of the service core obstruction is to increase the recirculation flow on the NW side

This first simulation revealed that the expected problem area behind the service core is well ventilated, showing no significant stagnation. When the windows on the leeward side are open, accumulation of heat and pollutants does not occur: the air flow in the adjacent corridor and over the meeting rooms is drawn towards the open windows.

In order to understand the effect of user operable windows on the flow pattern, a second simulation was performed with the user operable windows closed (case 3). Figure 8d shows a side view of the flow in the NW zone behind the meeting rooms and the service core for this case. Comparison of Figures 8c and 8d indicates a problem: the user-controlled window does not significantly affect the airflow in the occupied region.

This qualitative analysis was confirmed after post processing the results of these two cases. The average speed in the occupied zone only increases by 18% when opening the user-controlled lower opening. Opening the window does not significantly affect the flow pattern and the existence of the strong vertical recirculation region leads to accumulation of heat and pollutants in the windward bay.

With this initial window geometry, the users on the windward side do not experience significant changes in their local environment when opening the window, possibly leading to poor window operation decisions and consequent decreased cooling performance.

This first analysis revealed two aspects that could be improved. The flow from the operable windows could be better directed,

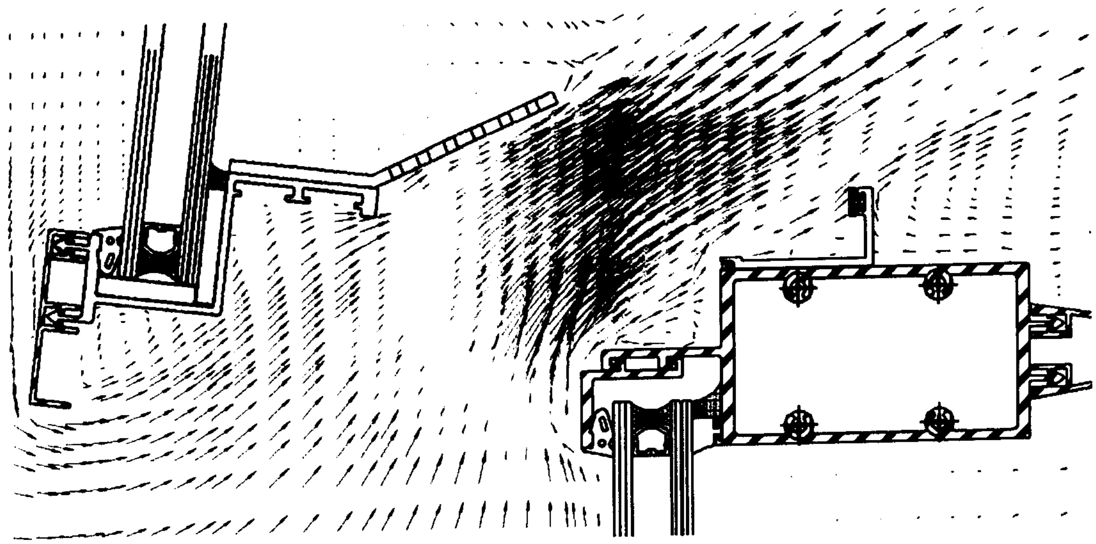

Figure 9 Simulation of inflow behaviour with the flow deflector

improving ventilation efficiency. Also, given the windy climate of the site and the ratio between average indoor and outdoor wind velocities, there is the possibility of reducing the maximum opening area.

5.1 Design of an inflow deflector for the user operable windows

In order to improve the heat and pollutant removal efficiency an inflow deflector for the user operable windows was designed. The flow deflector is incorporated in the bottom element of the moveable part of the window.

The inclusion of the flow deflector disrupts the recirculation by avoiding the attachment of the inflow through the lower window to the glass surface directly above the opening. It is desirable that the user operable opening has the maximum possible momentum flux, increasing its ability to affect the flow in the occupied zone, as discussed in the previous sections. An initial deflector design (not shown) led to a reduction in the opening area that reduced the overall opening area and diminished the influence of the lower opening on the flow in the occupied zone. In order to avoid these effects, several options were analyzed. Figure 9 shows the final deflector configuration, which significantly deflects the flow while allowing an adequate opening area.

5.2 Analysis of window opening requirements

A wind climate analysis shows that there is abundant potential for wind-driven ventilation. This is a consequence of both the base climate conditions and the good exposure and orientation of the façade. The building is sufficiently ventilated even with low wind velocities and, due to its particular geometry, small improvements in indoor flow distribution can have a significant impact on the efficiency of the ventilation system. An analysis of opening sizes and ventilation rates was performed, with the goal of identifying possibilities for reducing and simplifying the opening geometry. The analysis was performed by applying the orifice equation to each opening, using a value for the discharge coefficient for flow through a sharp-edged opening of 0.62.

The results, for external NW wind, are shown in Figure 10. The relatively small reduction in percentage of opened area between Cases 1 and 3 (see Table 2) results from the fact that, when only half the windows are

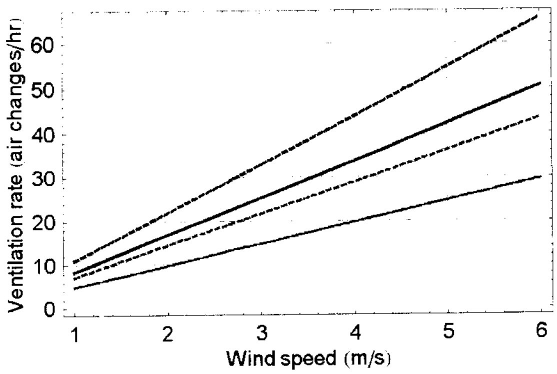

Figure 10 Variation of ventilation rate with wind speed (Cp = 0.9). Black dashed line: Case 1 (100%). Grey dashed line: Case 3 (66%). Black line: Case 4 (77%). Grey line: Case 5 (45%)

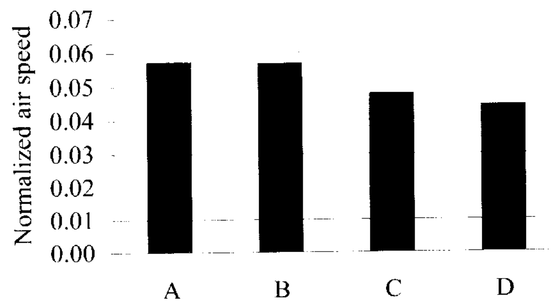

Figure 11 Normalized average air speeds for different configurations: A—normal fully open windows, B—same as case 1 but using porous furniture panels (90%, Yarn width 0.1 mm), C—same as 1 but with lower windows closed, D—same as case 1 but with one-half of the upper windows open. In all cases, the regions with maximum velocity in the occupied zone were close to the floor and had average velocities of approximately three times the occupied zone average

open, air flows through the triangular spaces on the side of the opening. With adjacent openings there is no flow through these spaces.

The reduction in flow rate that results from using only one half of the top window openings is not significant. Winds stronger than 2 m/s are very frequent, and for this wind speed, only the most closed configuration (Case 5) results in less than 10 air changes per hour. A NW wind of 3 m/s induces 22 or 16 air changes per hour when all the top windows or just one-half of them are open (Cases 3 and 5 in Table 2), respectively.

The analysis indicates that opening only half of the top windows, in combination with an improved airflow pattern, results in good ventilation. The upper windows are motorized, so this reduction has cost benefits. The use of alternating open and closed elements at the top of the exterior wall disrupts the two dimensionality of the system, contributing to increased mixing. As will be seen in the next section, the recirculations are still vertical, but become slightly less pronounced.

5.3 Effects of variable opening and office furniture configurations

CFD simulations were run in order to investigate possible negative effects of closing half the upper windows on the airflow pattern. The adoption of alternating open and closed elements required additional CFD simulations in order to investigate possible negative effects on the airflow pattern. The concerns were possible variations in air speed along the ceiling slab, caused by the non-uniform distribution of inlets, and the possibility of negative effects on the flow on the occupied zone, such as a significant air speed reduction.

Figure 11 shows the average air speed in the occupied zone, normalized using outside wind speed, for NW incidence and Cp = 0.9 for Cases A to D. The variations in average velocity when opening the lower windows are very small (Cases A and C in the figure). This is also the case shown in Figure 10 (Case D). The small reduction in occupied zone velocity is not significant, and can be easily offset by increase mixing and the improvements in airflow pattern that will be discussed later.

One of the many innovations in the design of the building is the specification of workstations/office furniture that is not only easily integrated in the space but also enhances the indoor environment. The furniture specifications produced by the building designers included:

1) Variable height in furniture panels depending on orientation (lower height for elements perpendicular to the mean flow).
2) A gap between the furniture panels and the floor (minimum 0.2 m).
3) Porous furniture panels (the porous panels are perpendicular to the cross ventilation flow and are meant to allow for light and air to flow through them). In order to improve privacy and acoustic insulation between adjacent workstations, porous panels were not used in the elements parallel to the mean flow.

The specified workstation geometry was included in the simulations. In addition, a simulation was performed to test the effects of porous panels. After preliminary simulations revealed that flow through the panels was small, it was decided to use the most porous sample: a woven screen regular mesh, with a yarn width of 0.1 mm and a porosity of 90%.[9]

The two main features of the flow around the workstations are: (i) the flow through the porous panel is small; and (ii) the flow accelerates under the vertical panels, leading to the highest speeds that can be found in the occupied space (in the windward zone).

The average velocity on the occupied zone in the simulation using porous panels is shown in Figure 11, case B. The effect of the panels in increasing flow in the occupied zone is negligible. This result is not surprising: air will always tend to flow through the unobstructed spaces of the occupied zone, and there are many areas where this unobstructed flow is possible. Any resistance to airflow leads to a deflection of the flow path into unobstructed zones, areas with no panels and the gaps between the panels and the floor.

6 Conclusions

A purely wind-driven ventilation strategy was selected for the building, based on the following results of a design analysis using EnergyPlus.

1) Natural ventilation is able to produce a level of thermal comfort that is likely to be acceptable to the occupants for all but a modest number of hours in a typical year.
2) Wind-driven ventilation slightly outperforms buoyancy-driven ventilation for the same opening sizes for this particular site.
3) On all but a few days, the nocturnal cooling of the building has to be limited in order to avoid uncomfortably cool conditions at the start of occupancy. The cooling performance of the building is then limited by the available thermal capacity and the effectiveness of the solar control, particularly on the NW façade.

The computational fluid dynamics simulations then led to several significant design changes.

1) Reduction in the amount of opening area used.
2) Change in the geometry of the automated opening area to alternating operable and fixed windows.
3) Change in geometry of the user controlled operable windows by introducing a flow deflector.

This airflow study reported here formed the basis for the design and testing of control strategy for the natural ventilation system, as described in a companion paper.[3]

The simulations and analysis presented here have resulted in increased confidence in the performance of the passive cooling and natural ventilation systems of the building as well as improvements to the design.

Acknowledgements

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