

DESIGN OF THE NATURAL VENTILATION SYSTEM FOR THE NEW SAN DIEGO CHILDREN'S MUSEUM

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ABSTRACT

This paper presents an analysis of the thermal behaviour of the new San Diego Children's museum and the subsequent development of a low energy climate control system. The museum is designed as a naturally ventilated building with no mechanical heating or cooling. The exhibition space consists of two galleries on the first and second floors and an atrium that extends over the two floors. There are openings on each floor, at the roof level and a solar chimney. The assessment of the ventilation system consisted of an initial analysis of the stack-driven ventilation. It was found that using only stack-driven ventilation led to predictions of significant periods of overheating in the museum. An analysis of the weather data then showed that there is a high correlation between the days of high temperature and a moderate prevailing wind – the sea breeze. Consequently, it was decided to use this wind to supplement the stack-driven flow. As a result additional openings were placed in the façade, and the solar chimney opening was oriented to be in suction during these periods. A BMS system and a control strategy were developed to optimize the performance of the building. As a consequence of these measures the number of predicted hot hours decreased significantly, and the results suggest that the building will operate satisfactorily. The tools used in this analysis were a specifically designed weather analysis spreadsheet, EnergyPlus with COMIS and computational fluid dynamics (CFD).

INTRODUCTION

The new San Diego Children's museum is designed by Rob Quigley, Architects and will be located in downtown on the corner of Front and Market, surrounded by a small park in front of the south facing main entrance, a large tower along the north and small buildings along the east and west sides. This surrounding topography allows for large solar incidence for most of the day and changes the incident wind characteristics. Figures 1 and 2 show rendering images and a sketch of the proposed design. One interesting feature is a solar chimney that is expected to promote buoyancy-driven flow that would come into the space through large, user-

controlled roll up doors at lower levels in the south facade. In an option made possible by the mild San Diego climate, no mechanical heating or cooling systems will be used in the main exhibition spaces where children will actively interact with artwork. The client played an important part in this sustainable design choice. The current museum facilities use natural ventilation, and the direct communication with the adjacent street that this system allows for is seen as an important feature in the museum.

The proposed museum exhibition space can broadly be divided into three zones: an atrium and two superimposed galleries, that are interconnected through large horizontal and vertical openings (see figure 1). Museum opening hours are 10am-4pm.

Ventilation air will be used to control indoor air temperatures in a VAV (variable air volume) principle driven by a combination of wind and buoyancy. In order to "organize" the airflow through the space and improve thermal comfort it was decided that the ventilation system would insert fresh outside air at low levels and exhaust at higher levels, achieving displacement ventilation (Linden, et al., 1990).

Early in the design assistance work it was decided that, in addition to user control, there was a need for an automated opening control system (Building Management System, BMS). Due to the importance of the chimney for ventilation airflow control, particular care was placed in defining the shape of the outlet from the chimney, in order to maximize wind-induced suction effects in the outlet surface.



Figure 1. View of the future San Diego Children's Museum

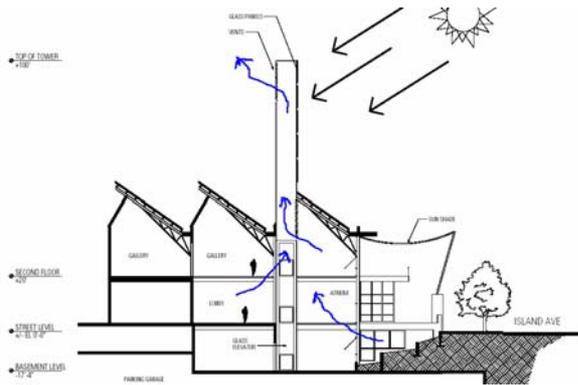


Figure 2. Schematic lateral view of the low energy cooling strategy proposed by the architect

The study of the passive climate control system followed a set of steps:

- I. Analyse weather characteristics that can be used to promote positive “resonance” between indoor and local climates. Changes will be proposed to the design in order to maximise this interaction.
- II. Analyse the effects of different skin compositions: single glazing versus double glazing, chimney geometry, roof insulation, etc.
- III. Refine existing window opening geometry and positions.
- IV. Define and predict the performance the window opening control strategy and control rules to be used by the BMS.

Using the following setoff tools:

- 1) A spreadsheet program with advanced programming functions for the weather analysis discussed in I.
- 2) A building thermal behaviour simulation tool (*EnergyPlus*) is used to address points II and IV.
- 3) Computational fluid dynamics simulations (CFD) of external wind driven flow.
- 4) Scaling analysis (point IV), to define when wind effects become important and should be considered by the control system.

WEATHER ANALYSIS

A detailed weather analysis was performed using two typical hourly weather years for San Diego (TMY), with the goal of identifying the design strategies that best use outside environment conditions to keep the indoor environment comfortable.

In order to address the problem of building cooling we first concentrated on warm days. Warm days were defined as days with maximum temperature above 79 °F, or days where the average between maximum (day time) and minimum (night time) temperature is above 77 °F. For these warm days the analysis focused on the outside temperature, wind velocity and direction. These are plotted in figure 3, with temperature (shown in Fahrenheit above 70, so

that $7=77$ °F), wind velocity (shown in mph) and wind direction (shown between -17 and 18 , where 0 is North, 18 is South, 9 is East and -9 is West).

Day time conditions

Figure 3 shows outside temperature, wind direction and velocity for warm days, during museum opening hours whenever the wind velocity was significant (above 3mph). This wind condition occurs for approximately 50% of these hours. Post processing of the data shown revealed that the wind blows from an angle (A): $330 > A > 200$ in 87% of the hours shown. Clearly, the prevailing winds on these warm days are from the northwest to the southwest.

The prevalence of these wind directions indicates that the best position for the chimney outlet is in the East face. This places the outlet in the leeside of the chimney for most of the time on warm days. This geometry, if carefully implemented, will generate suction of air through the chimney due to wind in 87% of the “hot” daytime. In this way the wind flow can assist the buoyancy-driven flow whenever necessary.

a subset of the data for days when the wind velocity is larger than 3 mph. Analysis of this data, restricted to days when there is significant wind, shows that the wind blows from the same sector (NW-S) for 76% of the time.

We conclude this analysis that it is possible to obtain improved chimney performance by using a high level opening on the East side. Additional gains can be obtained by inserting a small opening facing North.

SIMPLE THERMAL SIMULATION

In order to evaluate the starting point in cooperation with the design, a set of exploratory simulations was done using the building thermal simulation software tool *EnergyPlus* (Crawley et al., 2001). After analysis of the interior layout it was decided to use four zones (see figure 4): the atrium, the chimney and two galleries. All four thermal zones connect through the atrium and, in addition, the upper gallery and the chimney also connect directly. In this preliminary phase many geometric design details that have second order or little impact on the results are ignored or adapted to simplify the geometry. Comparison between the model in figure 4 and a more detailed model (see figure 9) fully confirmed the adequacy of these, apparently, crude approximations.

Internal gains were set to one occupant per 10m² and 10W/m² for other gains (lights and equipment). In order to perform these preliminary simulations there was also a need to develop a simplified control strategy that regulated the flow through the chimney in 10% adjustments depending on the indoor conditions. The aperture area was reduced if the interior was cold, and increased if the interior was both warm and warmer than outside.

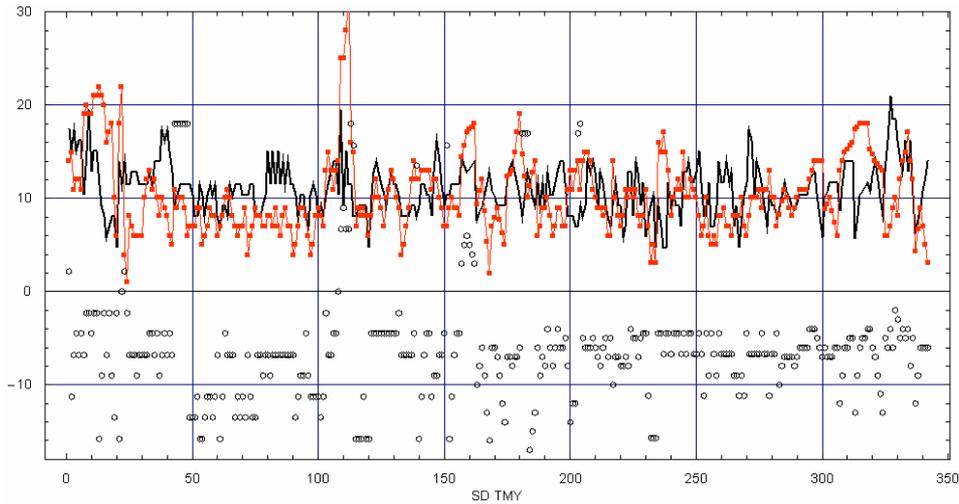


Figure 3. Hourly correlation during museum opening hours, between temperature (in red), and wind during warm days for two typical years of San Diego weather. Note that this analysis only considered hours of these warm days where the wind is significant i.e. when the wind velocity is above 3mph.

In this phase any wind effects were ignored since the pressure coefficients were unknown. In view of the results presented in Part II this approximation can be considered conservative since the proposed BMS system uses wind effects to increase airflow whenever it is advantageous.

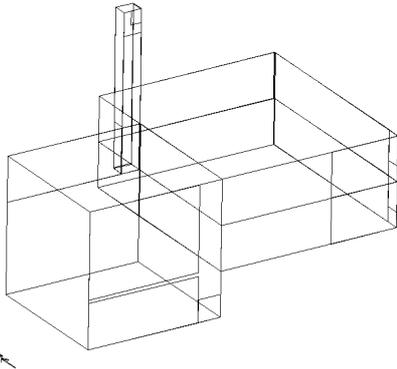


Figure 4. Base geometry used in the simplified EnergyPlus simulation.

The base scenario

Simulations were performed to examine the effects of: variable glazing composition, roof insulation and core chimney materials.

All simulations were performed using an automated control strategy that requires actuators on the bottom of the chimney and on one roll up door on each level (1 and 2) on the galleries. During museum operation hours, the atrium door on level -1 was considered to be always open. The results of these simulations are encouraging, indicating that the initial design provides a solid starting point for subsequent work, making good use of local climate conditions.

Effects of variations in building skin and chimney configuration

In order to quantify the effects of the different options for the building skin and the chimney, we

post processed the results by adding up the hours (during the occupied period) where the temperatures in the three zones of the museum interior are within five temperature intervals:

1. Cold: below 66°F
- 2 Comfortable: between 66 °F and 75 °F
- 3 Hot: between 75 °F and 81 °F
- 4 Very hot: between 81 °F and 86 °F
- 5 Too hot: above 86 °F

Table 1 gives the values (in percentage of hours in the five temperature intervals) found for the four alternative types of envelope defined for this study, shown here in increasing order of thermal insulation.

Table 1. The first case is the standard envelope, the second has double glazing, the third has double glazing with low emissivity and the last case uses twice the depth of fire proofing material (as a way of increasing the ceiling insulation).

Temperature regimes	1	2	3	4	5
Standard	5.6	55.8	23	13.5	2.1
Double GL	4.5	54.1	23.8	15	2.6
Double GL-LE	8.3	56.4	24.2	10	1.1
Standard+Double FP	5.7	56.9	23.3	12.2	1.9

There are two main results from the analysis shown in Table 1. The first is that comfortable conditions will occur for about 55% of the opening hours. We also expect that wind-driven ventilation will reduce the temperatures in range 3, so that they will fall in the comfortable range 2. Table 1 also shows that the main climate control problem is overheating (occurring approximately a third of the time). The internal temperature is too cold only in 6% of the hours (mostly in the early morning of a few cold days in the year). Therefore, the main concern for the

climate control system should be to prevent overheating.

The second result is that there are no significant gains from more expensive glazing options or additional ceiling insulation options. Improved indoor climate can be obtained by developing a control strategy that combines wind and buoyancy during day and night (when needed) to provide optimal indoor conditions.

Simulations were run in which black metal was placed in the interior of the chimney in order to absorb a larger fraction of the solar radiation. The results are shown in figure 5 and they suggest that the dark metal sheet can lead to a temperature increase of 10 – 20 °F in the internal surfaces of the chimney, thereby increasing the stack “power” without increasing the indoor temperature in the museum.

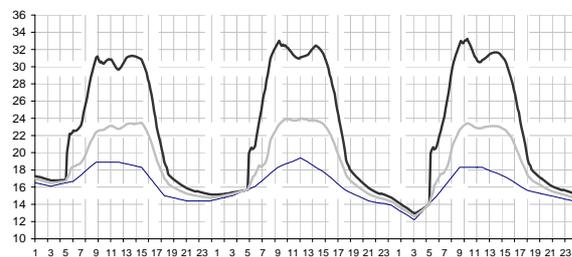


Figure 5. Simulation showing the outside air and chimney air temperatures for variable chimney composition. The black line showing the larger values is the mean radiant temperature for the chimney with a black metal plate insulated on the outside replacing the north face glazing. In grey the mean radiant temperature for the standard chimney. The thin line is the outside air temperature.

Results

In the Phase 1 analysis we conclude that the use of wind-driven ventilation in conjunction with stack may be possible in a significant percentage of the time using a single outlet configuration in the East face of the chimney. This is due to the prevailing west winds whenever the weather is warm.

The EnergyPlus simulations represent the worst-case conditions of no wind. They show (see Table 1) that the main problem is one of overheating which may occur for about one-third of the opening hours. For the rest of the time the building should work satisfactorily. The results also show there is little to be gained by making changes to glazing or the insulation. Higher temperatures in the solar chimney can be achieved by the insertion of black metal panels. There are several strategies that can be used to deal with the overheating problem.

(a) Use wind-driven ventilation. Our analysis shows that on warm days the prevailing wind direction is from the west (from approximately southwest to northwest).

(b) Use night cooling.

(c) Implement a control strategy that optimizes the ventilation flow.

Proposed changes to the initial design

After careful analysis and discussion of the results presented in the first part of this report, done in close cooperation with the design team, the following adjustments were made in the proposed design:

i. Insertion of dark corrugated metal sheets in the core of the chimney. As discussed above, higher temperatures can be achieved in the chimney core. The metal sheets should be placed inside the chimney, close to the North and East faces. The metal sheet placed along the east face is meant to increase chimney flow generating power in the afternoon.

ii. Definition of position and area of the chimney outlet surfaces. As a result of the weather analysis presented in section 1.1 the optimal orientation for the chimney outlet surfaces was defined (80% towards the East and 20% towards the north). In addition, the outflow area was defined so as to be no less than twice the inflow area, thereby making the flow restricting effect of the outlet negligible.

iii. Adjustments in position and size of several openings.

DEVELOPMENT OF AN OPENING-CONTROL STRATEGY

The second phase of the work consists in the development of a control strategy that considers both wind and buoyancy effects using the refined geometry that resulted from the analysis performed in part one.

Predictions of the coupled effects of wind and buoyancy in the bulk airflow in the interior of the museum are the main results that will be used in refining the control strategy. The simulation couples a refinement of the thermal simulation model used in part one (*EnergyPlus*) with results from computational fluid dynamics simulations (CFD). The next section describes the CFD simulations and the relevant results, followed by the presentation of the coupled simulation results.

CFD SIMULATIONS

Wind induced pressure in ventilation openings in the façade of buildings is typically represented using pressure coefficients C_p that depend on wind, building shape and adjacent building effects. Typically there are two predictive methods used to characterize wind induced pressure in the façade: a) perform a wind tunnel test using a scaled model of the site, b) perform a computational fluid dynamics simulation (CFD) using a simulation domain containing the building and relevant adjacent buildings.

The high cost of running wind tunnel tests is making the use of CFD with Reynolds averaged turbulence models ($k\epsilon$, Pope, 2000) more common. This increased use occurs in spite of known limitations when dealing with detachment and reattachment points in recirculating flows (such as the flow pattern in the wake of a wind impinged building). In the present case, resources made CFD the only choice. The considerable computation time involved in non-isothermal coupled internal-external flow simulations lead to the use of the following simulation strategy.

a) Perform CFD simulations for 8 incoming wind directions using a flow domain that includes adjacent buildings and wind velocity profile appropriate for an urban wind site (ASHRAE, 2001).

b) Use the pressure coefficients obtained in a) as input to an *EnergyPlus* simulation using a refined building geometry.

The simulation model in b) will be the base platform to refine the control strategy and obtain the final predictions of internal temperatures.

The simulations were performed using the commercial CFD package, PHOENICS version 3.3 (PHOENICS, 2000). The effects of turbulence were modelled using the standard $k\epsilon$ model. The result files were post processed in order to obtain the average pressure coefficients in each building surface. The incoming wind boundary layer characteristics used are meant to represent an urban/suburban wind profile (wind exponent 0.22, boundary layer thickness 370m [ASHRAE, 2001]).

Simulation geometry

The simulation geometry used is shown in figure 6 and 8. Towards the South there are no obstructions/other buildings within 300m. The simulation domain included two “layers” of existing or soon to be built buildings, which, in conjunction with the use an urban boundary layer inflow profile ensures adequate boundary conditions.

CFD simulation results

The large number of ventilation openings were grouped based on geometrical and pressure coefficient similarity. The rationale behind this grouping is to simplify the control hardware and control rules. The grouping used is:

- Group NAD: apertures N3A to N3D
- Group NEH: apertures N3E to N3H
- Group E: apertures E3A,B and E2A
- Group S: all doors facing south
- Group CH: the two apertures on the top of the chimney
- Group N1: single low level north facing aperture in gallery Level 1

The weighted average pressure coefficient for each aperture group is shown in table 2. Analysis of table

2 shows that wind induced pressure opposes the desirable flow pattern, inflow at low level and outflow at high level, whenever (see bold entries in the table) the wind blows from:

N, NE, SE and SW for group NAD.

E to SW for group E.

North for the south facing roll up doors.

NE or SE for the chimney top openings.

Table 2. Average pressure coefficients for the openings groups identified after analysis of the CFD results (multiplied by 100, for clarity).

Group	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
NAD	32	48	-3	10	1	15	-2	7
NEH	-5	-3	-2	4	2	6	0	-3
E	-15	0	12	88	12	30	-2	-24
N1	7	25	1	42	27	81	10	-4
S	-15	-5	-7	113	32	65	-5	-3
CH	-65	12	-4	55	-7	-4	-13	-26

Using a simple criteria to scale wind versus buoyancy generated pressures (see below) the opposing wind effects will be avoided by closing the aperture groups whenever the wind is not favourable (sufficiently strong and blowing from one of the unfavourable three directions).

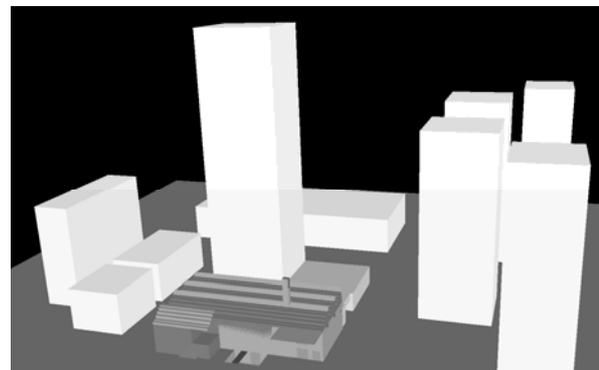


Figure 6. Geometry used in the CFD simulations. South view of the museum and adjacent buildings that influence the local wind field.

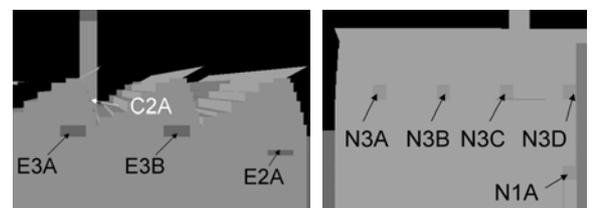


Figure 7. Geometry used in the CFD simulations. East (left) and a North (right) view of the museum showing the opening labelling notation that will be used in the control system.

Analysis of on site wind measurements

The simulations that are shown below will be performed using a weather data measured in the San

Diego airport at 10m height in open terrain conditions. On-site wind calculations were performed in the most unobstructed location on the site: the top of the solar chimney. Figure 8 shows the relation between wind at the airport and CFD wind predictions using a virtual probe located 2m above the top of the chimney (dark arrows in the figure).

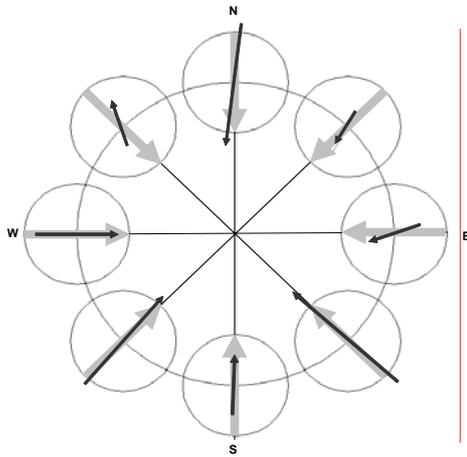


Figure 8. Relation between wind conditions measured in the airport (grey arrows) and CFD predicted measurement results using a probe situated 2m above the top of the solar chimney (black arrows).

In most cases the wind direction at the site is close to that at the airport and is not deflected significantly by the surrounding buildings. However, the NW wind direction may give a wind direction that is opposite to the airport-wind direction. As can be seen from figure 8, this reversal in wind direction is a result of the museum being in the wake of the tall buildings on the north and western sides in that case. In this case the reversed wind direction is taken into account but, in view of other approximations used, the other small changes in wind direction shown figure 8 will be neglected.

The results in figure 8, show that there is change in the magnitude of the on-site wind speed compared to that at the airport. In order to account for this change a magnitude scaling factor will be applied to site measured results so that the pressure coefficient table shown above can be used directly. This site-measurement conversion coefficient is defined as

$$C_{SM} = \frac{V_{WA}^2}{V_{WS}^2} \quad (1)$$

where: V_{WA} wind velocity measurement at the airport (in m/s, as taken from the weather file used in developing the control strategy shown below). V_{WS} wind velocity measurement on site (m/s).

VENTILATION OPENING CONTROL PRINCIPLES

The control strategy for the San Diego Children's Museum natural ventilation system is based on a

VAV approach. As a function of measured internal and external temperatures, the airflow will be adjusted to optimize indoor conditions. Outdoor airflow through the museum is driven by a combination of wind and buoyancy. The building management system (BMS) uses data from a weather station located in the top of the chimney, measuring: temperature, humidity, wind speed and direction.

Strategy for wind driven flow usage

Table 3 shows the basic strategy for dealing with wind driven flow usage in the control system. Because the museum space is composed of several interconnected spaces (the atrium, the exhibition galleries in Level 1 and 2, and the chimney) flow control is a delicate task. In this type of connected multi-zone flows, an increase in overall flow rate may result in temperature increase or decrease in one of the interconnected zones as it receives more or less exhaust air from an adjacent zone or direct outside air.

Wind-driven flow must be considered for two reasons: wind can assist buoyancy in providing the desired airflow (particularly during the summer period), and wind can disrupt the internal stratification and cause inflow through higher levels or even greatly reduce overall airflow rate.

Since internal flow will be driven by buoyancy, the opening strategy should avoid inflow at high levels. For this purpose, total inflow and outflow areas should be balanced. Any asymmetry in opening area should tend towards a larger inflow area so that a significant positive pressure difference occurs at higher levels.

Table 3. Strategy for wind driven flow usage.

Season	Wind assistance	Wind related control strategy
Winter	None	Avoid conflict with stack
Mild	During daytime, if needed	Use wind to assist stack
Summer	During daytime and night time, if needed	Use wind to assist stack or, use wind dominated airflow to increase night time structural cooling capacity

Deciding when wind effects must be considered by the BMS

In a vertically stratified space, such as the interior of the museum, evaluating buoyancy generated pressure difference at inflow and outflow openings is a complex task involving vertical integration of the density difference between indoor and outdoor air. In the present case this evaluation is more complex since air can enter and exit the space at different

levels and in different zones. Although evaluating wind-driven flow (given that the pressure coefficients are known) is simple, its interaction with buoyancy effects is difficult to model since buoyancy pressure is difficult to obtain. In view of this difficulty, and taking into account other uncertainties in the modelling process, it was decided to use the following simple scaling relation between wind and buoyancy

$$S_{WB} = \frac{1/2 \rho |C_{Pa}| C_{SM} V_{WS}^2}{\Delta T \beta g h}, \quad (2)$$

where: S_{WB} is the non-dimensional that is used to scale wind and buoyancy effects. ρ air density (Kg/m^3). C_{Pa} wind generated average pressure coefficient (for a given direction and aperture group it is the value in bold face in table 3). C_{SM} Conversion factor for site measurements (see figure 8 and (1)).

V_{WS} wind velocity measured on site (m/s). ΔT representative temperature difference between inside and outside (K). β volume thermal expansion coefficient for air (1/K). g average acceleration of the earth gravity field (m/s^2). h representative building stack height (m).

Expression (2) is evaluated for each aperture group whenever the wind is expected to generate a positive pressure at an outlet (or negative at an inlet), potentially disrupting the thermal stratification (see entries in bold face in table 2).

The denominator of (2) contains two unknown factors, the representative temperature difference (ΔT) and building stack height (h). The representative temperature difference will be obtained using the following expression:

$$\Delta T = \text{Minimum} \left(\frac{T_A + T_{G1} + T_{G2} - T_{OUT}}{3} \text{ or } 2 \right) \quad (3)$$

where: T_A is the average air temperature in the atrium ($^{\circ}\text{C}$). T_{G1} is the average air temperature in gallery level 1 ($^{\circ}\text{C}$). T_{G2} is the average air temperature in gallery level 2 ($^{\circ}\text{C}$). T_{OUT} is the outdoor air temperature ($^{\circ}\text{C}$).

Decision rules used by the building management system

Table 4 shows the BMS decision rules as a function of measured temperatures. These rules are implemented in the control strategy using an *if then else* structure, shown below. The control strategy, using degrees Fahrenheit is, *during daytime*:

```

IF (  $T_{IN} > 76$  ) THEN
IF (  $T_{OUT} > T_{IN}$  ) THEN Decrease mode number by 1
ELSE Increase mode number by 1 END
IF (  $T_{IN} < 63$  ) THEN IF (  $T_{OUT} > T_{IN}$  )
THEN Increase mode number by 1
ELSE Decrease mode number by 1 END

```

During night time:

```

IF Avrg.  $T_{IN}$  during daytime  $> 76$  °F AND  $T_{IN} > T_{OUT}$ 
THEN Increase mode number by 1
ELSE Decrease mode number by 1 END

```

Under certain conditions, increasing or decreasing the aperture area may be impossible. For example *under high wind or heavy rain overall aperture area must be restricted*. In order to ensure minimum outside air a minimum aperture area is imposed. This area depends on indoor and outdoor conditions.

Table 4. Flow rate decision rules as a function of measured temperatures.

Temperature relation	Flow rate adjustment
$T_{OUT} > T_{IN}$	Decrease if interior is warm, increase if interior is cold, maintain if conditions are comfortable
$T_{IN} > T_{OUT}$	Increase if interior is warm, decrease if interior is cold, maintain if conditions are comfortable

COUPLED SIMULATION OF SYSTEM PERFORMANCE

Figure 9 shows the refined building geometry used to test and refine the control strategy in the coupled EnergyPlus simulation. The control rules presented above where implemented in Fortran and a special version of the EnergyPlus source code was compiled, allowing for testing of the control rules in a simulation using the pressure coefficients obtained using CFD.

A sample of the results of the coupled simulation is shown in figure 10. Here the BMS selected opening mode is shown in small black squares (showing opening-mode values between 1-closed and 9- fully open). In the first two of the seven days shown the building remains mostly closed, and the BMS tries to conserve internal heat. As the outside temperature increases in the following days the opening mode values progressively increase during the day until, in the last days, night cooling is used, leading to large opening modes being used at night.

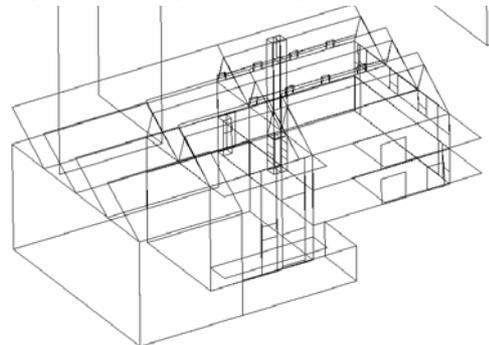


Figure 9. Simulation geometry used in EnergyPlus in the second phase of thermal simulation.

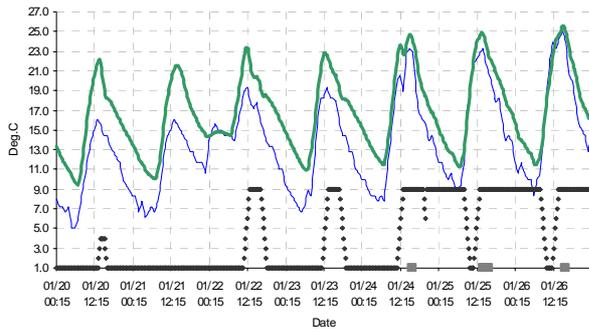


Figure 10. Indoor and outdoor temperatures for a sequence of increasingly warmer days. The thick green line is the average indoor temperature. The thin blue line is the outdoor temperature. The black squares show the BMS opening mode selected in a given time step. The grey squares show times when the user operated roll up door where open.

At 9am every day the BMS system progressively selects mode 1 so as to create sufficiently warm conditions before the 10am opening hour every morning. User control of the south facing roll-up doors was modelled as discussed above, the result is shown by the large grey squares in the figure: whenever indoor temperature goes above 23°C the users (museum staff) open the roll up doors that will then only be closed at 4pm (museum closing time). This simulation shows that on cool days the control strategy keeps the interior of the museum at a (warmer) comfortable temperature, and on the warmer days it remains close to the ambient temperature.

Table 5 shows the summary results of the coupled simulation carried out over the 2 TWY. The results in row 2 exclude wind and user control and are shown here for comparison. The final system performance predictions are shown in row 3. The 7% reduction in “Hot” and “Very hot” hours is remarkable. A small increase in “Cold” hours occurs as a result of the user control of the large roll-up doors. On some days the space warms up quickly in the morning and the roll-up doors are opened, and then later in the day the temperatures become excessively cold. However, the roll-up doors are still only closed at 4pm for safety reasons and so the interior overcools later in the day.

Table 5. Results of the coupled simulation using variable control and flow driving mechanisms.

Percentage of hours where T_{IN} is:	$T_{IN} < 66$ (F) Cold	$66 < T_{IN} < 75$ (F) Good	$75 < T_{IN} < 81$ (F) Hot	$81 < T_{IN} < 86$ (F) Very hot	$T_{IN} > 86$ (F) Too hot
BMS controlled Stack driven flow	5.8 %	56.5 %	23.7 %	12.1 %	1.9 %
BMS and USER controlled Stack and wind driven flow	6.6 %	66.0 %	20.4 %	5.2 %	1.8 %

CONCLUSIONS

The design assistance work presented in this report was successful in improving the performance of the natural ventilation climate control system for the new San Diego children’s museum. Comparison of the second row in table 1 with the third row in table 9 reveals a significant reduction in overheating hours which was the main problem of the initial design.

This reduction was obtained by modifying the opening geometry, adding additional openings, heat collecting surfaces (in the chimney core), and adopting an adequate opening geometry that maximized positive effects of wind driven flow, while maintaining vertical thermal stratification in the space.

A further feature of naturally ventilated buildings is that occupants exert significant control by opening or closing windows and doors. Consequently, the effectiveness of the ventilation system depends on their behavior and there is a need for education and training of the building occupants in order to achieve the best performance of the building.

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