

Effects of window size and thermal mass on building comfort using an intelligent ventilation controller

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Abstract

A prototype microcomputer-controlled thermostat was developed that can manage airflow according to cooling the needs in a building and the resources in the environment. This intelligent control system measures both indoor and outdoor temperature and uses decision rules to control a whole-house fan, in addition to the furnace and air conditioner. No such residential thermostat is currently commercially available. This paper presents the controller strategy that optimizes cooling with outdoor air. This paper also quantifies the effects of modifying the amount of thermal mass and the window area on indoor comfort when using this controller. These test confirm that smaller windows and more mass performed better than larger windows and less mass, and that higher volumes of controlled ventilation outperformed fixed ventilation rates.

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1. Introduction

A passive cooling system is capable of transferring heat from a building to various natural heat sinks. Cooling by ventilation to the atmosphere is the simplest way to remove heat from buildings and probably the most common passive cooling system.

Ventilation can be used for three completely different functions in a building: maintaining indoor air quality (IAQ), cooling the human body and cooling the structural mass of the building. Each of these has different requirements that affect the building and the ventilation systems. In this paper we are mainly concerned with structure cooling. Good IAQ is usually an indirect positive product of ventilation systems. Comfort ventilation is an additional resource that can be implemented

to extend the comfort zone upward beyond the limit for still air. Structure cooling can be implemented during occupied daytime hours, sometimes called economizer cooling, or more usually as nocturnal ventilative cooling, when outdoor air temperatures are lower and more suitable for sensible cooling.

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. This ventilation system can be either fan forced or natural through windows that are opened and closed at appropriate times. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates. Night ventilation reduces internal maximum temperatures, peak cooling loads, and overall energy consumption and

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has been well documented (Cook, 1989; Givoni, 1994; Stein and Reynolds, 1992; Santamouris and Asimakopoulos, 1996; Allard and Santamouris, 1998).

The applicability of nocturnal ventilative cooling is limited to a certain range of conditions (Givoni, 1994) which are a function of the needs of the occupants and climatic conditions. Occupants affect decisions such as opening or closing of the windows during the night and the desirable comfort levels. The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level, which determines the upper temperature limit of indoor comfort with still air or with air movement (Geros et al., 1999). Since the outdoor daily temperature swing increases as the air humidity is reduced, the humidity of the air is one of the practical determinants of the applicability of different ventilation strategies. Even though this strategy is usually not considered effective in warm humid climates, some authors (Machado and La Roche, 1999; Szokolay, 2000) have explored the implementation of nocturnal ventilative cooling as a passive cooling option for buildings in warm humid climates.

The main parameters that determine the efficiency of night-ventilation can be classified in three broad groups: climatic parameters, building parameters and technical parameters of the technique (Blondeau et al., 2002).

In relation to the climatic parameters, several authors have proposed calculation methods, predictive equations or rules of thumb to predict performance with different amounts of mass, ventilation rates, temperature swings or outdoor average temperature. Givoni states that the indoor maximum temperature in night ventilated buildings follows the outdoor average temperature and proposes formulae to predict the expected indoor maximum temperature with different amounts of mass and insulation (Givoni, 1992; Givoni, 1998). Stein and Reynolds propose rules of thumb and calculation methods to determine the amount of heat that can be removed from a building with a given amount and distribution of mass, during a typical day, for specific design conditions (Stein and Reynolds, 1992). Shaviv proposes a tool to predict the decrease in the maximum temperature from the diurnal temperature swing as a function of the night ventilation rate and the amount of mass (Shaviv et al., 2001). Computer programs, like HEED, allow users to determine the effects of mass, ventilation rates and insulation on the indoor air temperature or the amount of air conditioning required to maintain a specified comfort temperature (Milne et al., 2003).

In relation to building characteristics, the requirement is usually a minimum amount of thermal inertia, generally defined as a minimum building mass (Givoni,

1992). The existence of important thermal-structural mass increases the efficiency of the technique since the inertia of the building is increased and the effect of night ventilation can be observed in the next day's indoor temperature profiles, with a lower and delayed peak indoor temperature (Geros et al., 1999). The interior planning of the building also plays a very important role, determining how unobstructed is the flow of the air through the building (Geros et al., 1999).

The technical parameters related to the efficiency of night ventilation deal with the operation period and air change rate. There is agreement on the fact that heat gains by conduction through the building fabric, solar gains through window glazing, infiltration from warm outdoor air and internal gains from equipment and occupants must be reduced. It is also well known that higher air changes are better than lower air changes, but there is no agreement on the ideal air change rate, and values range from 8 to 20 air changes per hour (Blondeau et al., 2002).

The operation of the ventilation systems in buildings (windows or fans) is usually controlled by timers or the occupant of the space who must rely on his/her experience, or by thermostats that only measure indoor temperature. Little has been done on techniques to improve the performance of these ventilation controllers. Some authors (Eftekhari and Marjanovic, 2003) are developing a fuzzy logic controller that monitors outside and inside temperatures together with wind velocity and direction, to open or close a window in various degrees, to ventilate a building.

Even though their potential for cooling is well known, natural and hybrid ventilation strategies have not been investigated in the United States to the same extent as in Europe (Spindler et al., 2002). This is partly because typical buildings in the United States, especially houses, do not have much mass to act as heat sinks, and the additional mass needed for ventilation is also associated with an increase in costs.

In previous papers we developed and tested a smart controller that optimizes the use of forced ventilation for structure cooling in a building (La Roche and Milne, 2001, 2002). This controller used a set of decision rules to control a fan to maximize indoor thermal comfort and minimize cooling energy costs using outdoor air, the greatest potential source of free cooling energy in most California climates. This controller knows when to turn the fan on and off to cool down the building's interior mass so that it can 'coast' comfortably through the next day. Thus, the need for air conditioning can be greatly reduced or even eliminated. But the performance of this system can be seriously compromised if certain design considerations are not taken into account regarding the amount of mass and the control of solar radiation. The effects of mass and window size, under different air change rates, on the system were determined.

2. Experimental system

The experimental system consists of a microprocessor controller connected to thermistors that measure temperature, a laptop computer connected to it which contains the control programs and collects and stores experimental data, the two test cells and an active ventilation system, which consists of a 4-in. inlet and on the outlet side a 4-in. constantly running fan (Fig. 1). The inlet damper is opened and almost closed in the experimental cell by a signal from the microcomputer, and the damper is fixed in an “almost” closed position on the control cell to also allow the same controlled amount of infiltration in each cell (0.7 air changes per hour).

Two identical test cells were built simulating the characteristics of typical California slab-on-grade houses. Only the characteristics that could affect the thermal performance of the ventilation system were incorporated in the cells: the insulation level, the brick slab and the glazing. Another simplification was that the cells only had a south-facing window so that they would receive the same amount of radiation at the same time. The cells are 122 cm (4 ft.) wide by 244 cm (8 ft.) long and 244 cm high, and are oriented with the longest facade towards the east and west (Fig. 2). The cells have 7.6 cm (3 in.) foam R12 insulation on the outside and 6.4 mm (1/4 in.) gypsum board inside the walls and roofs with a U value of $0.43 \text{ W/m}^2 \text{ K}$ in the walls. The east and west walls have additional shading provided by an insulation panel separated 8 cm from the wall. A calibration series, with both cells in identical conditions demonstrated that these panels eliminated the distortion caused by solar radiation in the morning and afternoon. The floor is hardboard placed on top of an insulation panel and the roof has two layers of insulation with a U

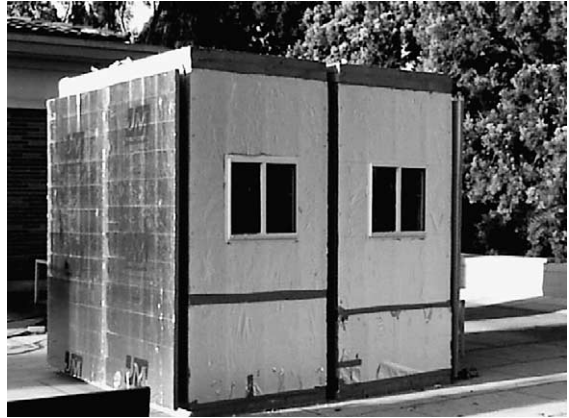


Fig. 2. The test cells.

value of $0.22 \text{ W/m}^2 \text{ K}$. There is a $61 \times 61 \text{ cm}$ ($2 \times 2 \text{ ft}$) double pane window on the south side with a solar heat gain coefficient of 0.72 and a U value of $4.25 \text{ W/m}^2 \text{ K}$ ($0.75 \text{ Btu/h ft}^2 \text{ }^\circ\text{F}$). The area of the window is 37 m^2 (4 ft^2) for a ratio of the glazing to floor area of 12.5%. The walls and windows are carefully sealed so that infiltration is controlled only by the fan and damper system.

One of these cells, with the smart operable venting system is the “experimental” cell in which the air change rate varies between 0.7 and 3.9 air changes per hour. The other cell is the “control” with a fixed ventilation rate of 0.7 air changes per hour.

Different control rules were tested to determine which was more efficient in using outdoor air to achieve thermal comfort. The controller programs that were tested are simple enough so that they can be built into a thermostat and the homeowner does not need to change or even understand them. Four variables were used to determine the appropriate air change rate: indoor air temperature, outdoor air temperature, comfort low and comfort high. The first two measure the air temperature and determine the need for cooling. If the indoor temperature is higher than the outdoor temperature the airflow rate increases by opening the damper and if the indoor temperature is higher than the outside temperature, the damper is closed to reduce the airflow rate. Comfort low and comfort high set the upper and lower limits of the comfort zone and determine the air change rate accordingly. If the air temperature is above the comfort zone it is too warm to provide cooling and if it is below the comfort zone, no additional cooling is needed. A wider comfort dead band reduces energy needs for cooling.

Various control strategies were tested with different relationships between the variables (some rules did not use all variables), air change rates, and values for comfort low and comfort high, in the summer of 2000 and 2001 and presented in several papers (La Roche and

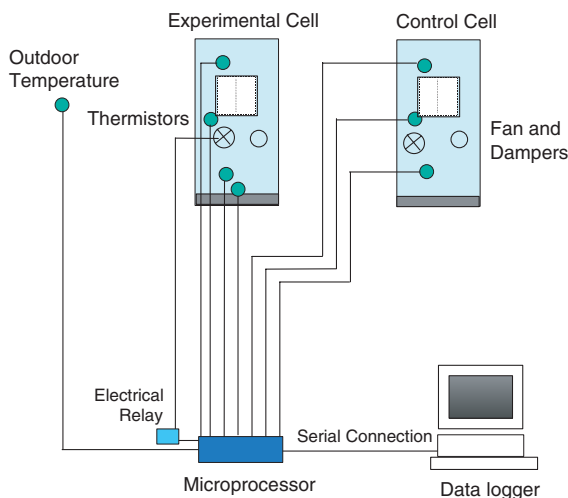


Fig. 1. The experimental system.

Milne, 2001, 2002). The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell is expressed in Eq. (1):

$$\text{If } t_o < t_i \text{ and } t_i > C_{f_low} \text{ and } t_i < C_{f_high} \text{ then fan ON else fan OFF} \quad (1)$$

where t_o is the temperature outside; t_i is the temperature inside; C_{f_low} , is comfort low at 18.33 °C (65 °F); and C_{f_high} is comfort high at 25.55 °C (78 °F). This is the rule that was then used to determine the effects of the mass and window size.

3. Experimental results

Several tests were performed in the summer of 2002 and are presented here to explain the effects of modifying the amount of mass, the size of the window and the air change rate. The window size was modified from its full size position by also covering all or half of its surface with an opaque wall insulation panel. Each cell has 106 cement bricks distributed evenly in the floor simulating a concrete slab. The bricks are 4×8×2.5 in. and are spread evenly over the surface of the floor with a thickness of 2.5 in. In series 6 and 7, 110 more bricks were added around the lower walls of the experimental cell to study the effect of additional mass.

There are four thermistors in the experimental cell, three thermistors in the control cell and one thermistor outside in the shade. In each cell the thermistors are placed in the middle of the cell, but at different heights. The lowest one is 5 cm (2 in.) above the bricks, the middle one at 137 cm (54 in.) and the highest one at 231 cm (91 in.), which is 10 cm below the ceiling. In the experimental cell an additional thermistor measures the temperature of the mass. Only the air temperature at a

height of 137 cm is reported in this paper. The series are described in Table 1.

3.1. Series 1: 50% window compared to 100% window

In the first series, initiated in May 22, 2002, the area of the window in the experimental cell is 0.185 m² (2 ft²) and the area of the window in the control cell is 0.37 m² (4 ft²). The venting system is set at a fixed infiltration rate of 0.7 air changes/hour, and the amount of mass is 106 bricks, or about 345 kg (760 lbs) (Fig. 2).

During the day, the values of the maximum temperatures in the control cell are an average of 1.4 °C higher than in the experimental cell due to the extra solar gain through the windows of the control cell (50% size window versus 100% size window). At night, the temperatures inside both test cells are very similar, because the difference in heat loss is not significant. Also, because the solar gain in the experimental cell was lower than in the control cell, the minimum temperature inside this cell is slightly lower, an average of 0.4 °C than the minimum temperature in the control cell. But because both air change rates are low, the minimum temperatures in both are more than 3 °C higher than the outdoor minimum (Fig. 3).

3.2. Series 2: no window compared to 100% window

In this series, initiated in May 29, 2002, the window is eliminated in the experimental test cell. The difference between the daytime maximum temperatures in the control cell and the experimental cell is 2 °C, which is 0.6 °C more than in the first series (Fig. 4). This is due to the additional solar gain through the windows of the control cell (0% window versus 100%-sized window). At night the minimum temperatures inside both cells are similar,

Table 1
Series presented in this paper

Series and Date	Difference from previous (experimental cell)	Experimental Cell	Control Cell
1. May 22, 2002	Window 50%	Window: 50%, Air change: 0.7, Mass: 760 lbs. brick	Window: 100% Air change: 0.7 Mass: 760 lbs. brick
2. May 29, 2002	Window eliminated	Window: 0%, Air change: 0.7, Mass: 760 lbs. brick	Same
3. June 20, 2002	Window added controller activated	Window: 100%, Air change: 0.7–3.9, Mass: 760 lbs. brick	Same
4. July 15, 2003	Window 50%	Window: 50%, Air change: 0.7–3.9, Mass: 760 lbs. brick	Same
5. June 11, 2002	Window eliminated	Window: 0%, Air change: 0.7–3.9, Mass: 760 lbs. brick	Same
6. August 17, 2002	Mass added	Window: 0%, Air change: 0.7–3.9, Mass: 1560 lbs. brick	Same
7. August 8, 2002	Window added 100%	Window: 100%, Air change: 0.7–3.9, Mass: 1560 lbs. brick	Same

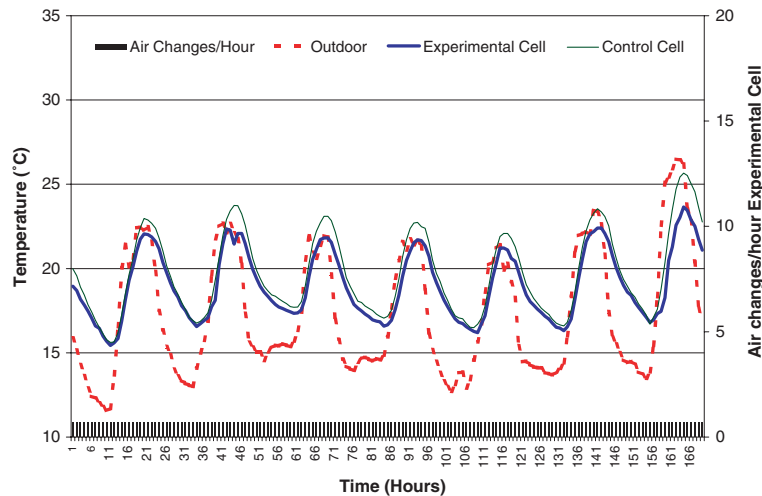


Fig. 3. Outdoor, experimental and control cell temperatures in series 1, 50% window in the experimental cell compared to full window in the control cell, with the smart controller off in both cells.

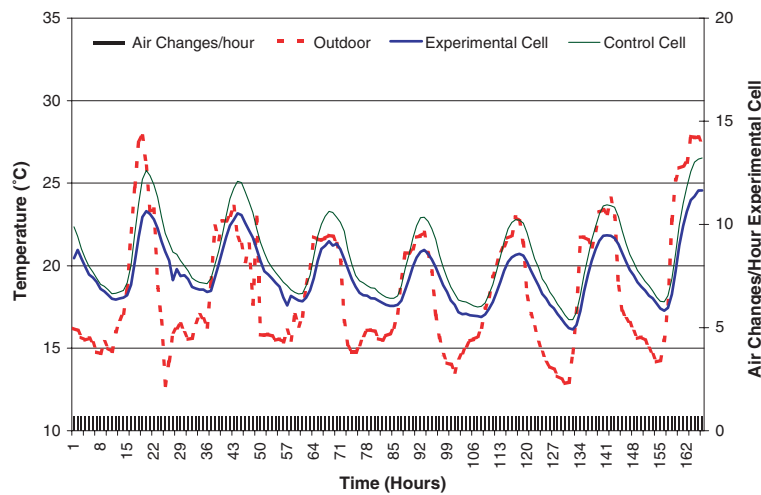


Fig. 4. Outdoor, experimental and control cell temperatures in series 2, 100% window compared to no window with the smart controller off in both cells.

with a 0.5 °C difference because they have the same air change rate and the difference in heat loss through the cells is not significant.

3.3. Series 3: window and vented

In this series initiated in June 20, 2002, both test cells have 100% windows and the same amount of mass. The only difference between both cells is that the smart controller for the venting system in the experimental cell is activated, so that the air change rate is higher when determined by the controller.

Since both cells have their windows at 100% of their size, the difference between the daytime maximum temperatures in the control cell and the experimental cell is due to the effect of the thermal inertia of the mass, which is cooled at night by ventilation (Fig. 5). The difference is not more noticeable because of the solar gains through the unshaded window. At night, when the smart controller is operating in the experimental cell, the minimum temperature inside this cell is much lower than the temperature in the control cells and closer to the outdoor minimum, because of the ventilation effect of the smart controller. Some days the indoor temperature is

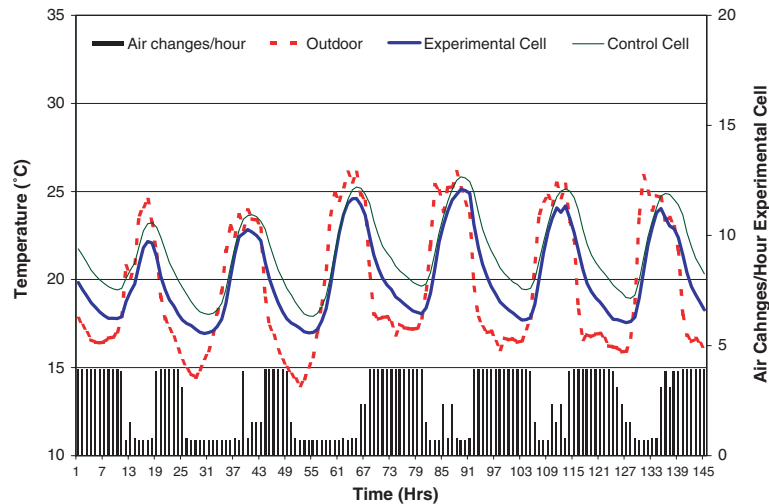


Fig. 5. Outdoor, experimental and control cell temperatures in series 3, 100% window in both cells with the smart controller operating in the experimental cell.

not lower because it reaches the lower level of the comfort band.

3.4. Series 4: window reduced 50%

In this series initiated in July 15, 2003, the window of the experimental cell is reduced to 50% of the original size. Because the window is smaller, the maximum temperature in the experimental cell is lower than in the control cell and the difference between the maximum temperatures in both cells increases to 1.8 °C, compared to 1.4 °C in the previous series (Fig. 6). At night, the minimum temperatures in the experimental cell are

lower than those in the control cell and closer to the minimum temperatures at night.

3.5. Series 5: window eliminated

In this series initiated in June 11, 2002, the window is eliminated in the experimental cell. Because now there is no window in the experimental cell, its maximum temperature is still lower than the control cell. The difference between the maximum temperatures in both cells increases to 2.2 °C, compared to 1.4 °C in the previous series (Fig. 7). At night, the minimum temperatures in the experimental cell are lower than those in the control

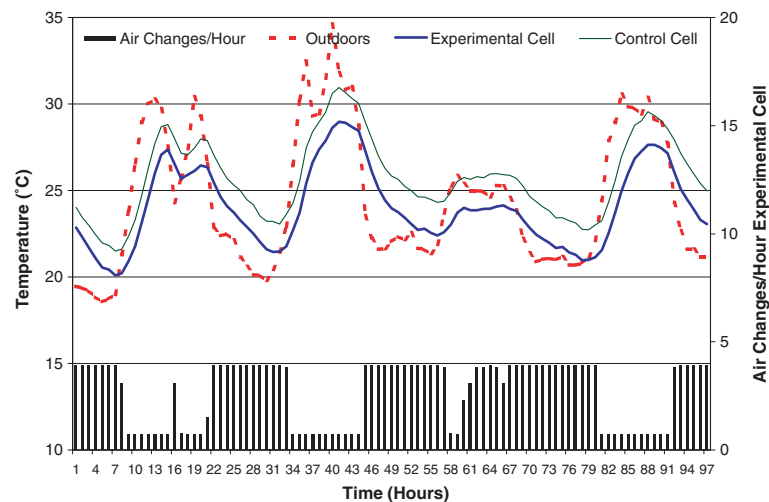


Fig. 6. Outdoor, experimental and control cell temperatures in series 4, 50% window compared to no window with the smart controller on in the experimental cell.

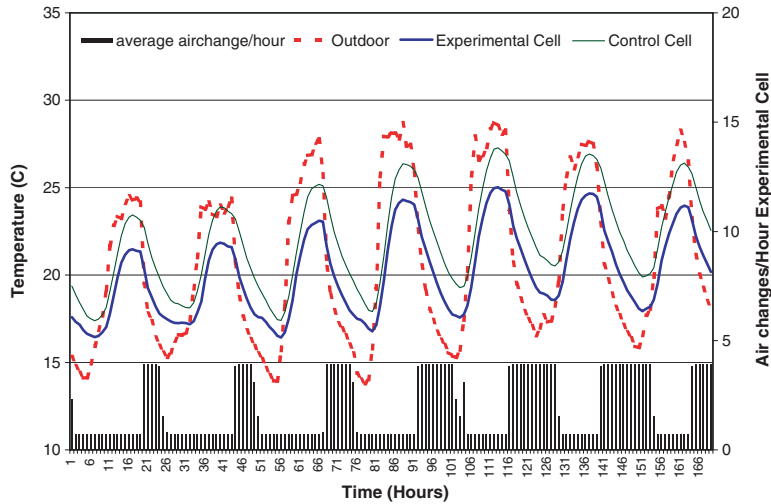


Fig. 7. Outdoor, experimental and control cell temperatures in series 5, with 0% window in both cells with the smart controller operating in the experimental cell.

cell, but not quite as low as the outdoor minimum temperature because the damper closes when the air temperature inside the cell drops below 18.33 °C. If comfort low was set at a lower value, this test cell would have a lower maximum temperature the next day, but the temperature inside the cell would also be cooler during the night, and drop below the comfort zone.

and the maximum temperature in the control cell is now 3.1 °C. Even though the outdoor temperature sometimes rises above 28 °C, the internal temperature inside the experimental cell is never above 25 °C (Fig. 8). The minimum temperatures in the experimental cell are also lower than in the control cell because of the effect of the fan controller.

3.6. Series 6: additional mass

In this series, initiated in August 17, 2002, 110 bricks are added to the experimental cell. The difference between the maximum temperature in the experimental cell

3.7. Series 7: window added

In this series, initiated in August 8, 2002, the window is again set to the full size of 4 ft² in the experimental test cell while maintaining the extra mass. The maximum

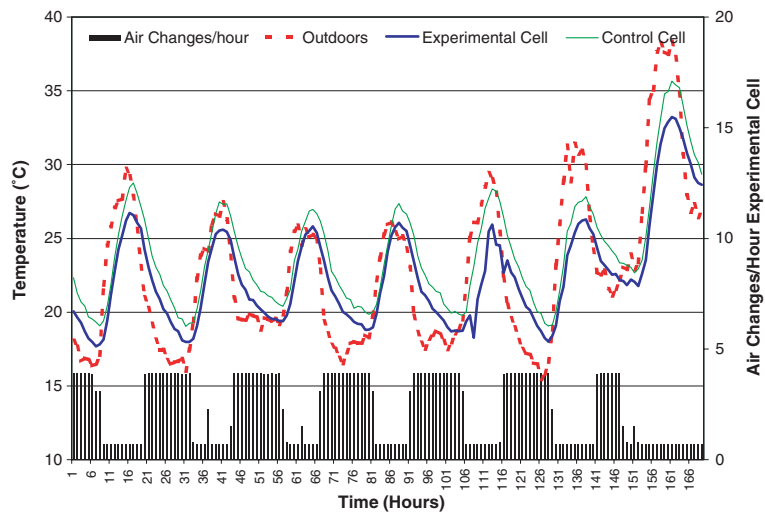


Fig. 8. Outdoor, experimental and control cell temperatures in series 6, 0% window in both cells with the smart controller on in the experimental cell and additional mass.

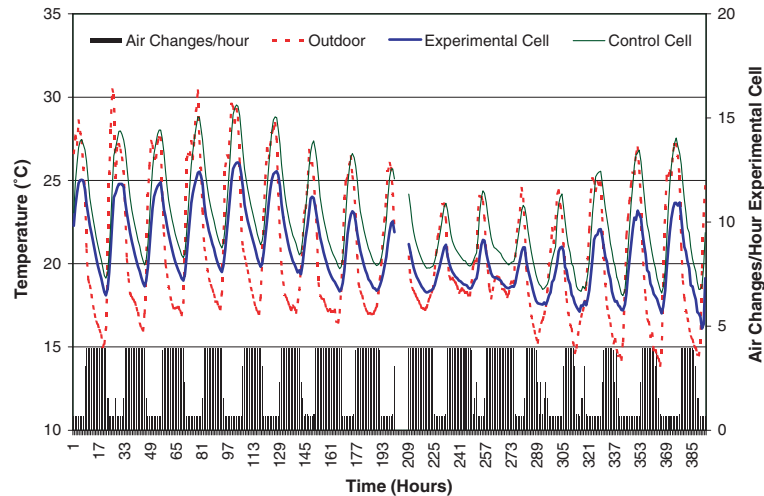


Fig. 9. Outdoor, experimental and control cell temperatures in series 7, 100% window and smart controller on in the experimental cell and additional mass.

temperatures inside both cells are closer together than in the previous series (1.8 °C) due to the solar gains through the window that reduces the cooling effect of the system. Minimum temperatures are always lower than the minimum temperatures in the control cell (Fig. 9).

4. Discussion

Three variables are used to evaluate the performance of the different series: the comparison of the maximum temperatures, the temperature difference ratio (TDR) and the percentage of overheated hours.

4.1. Temperature differences

Comparison of the average maximum temperatures in the two cells is indicative of the performance of the system (Table 2). The larger the difference between the maximum averages in both cells, the better the performance of the experimental cell.

The experimental test cell always has a lower average maximum temperature than the average maximum outdoors and in the control cell. The largest difference between the average outdoor maximum temperature in both cells is 3.1 °C in series 6 that has no window and more mass with an intelligent controller. Note that series 2, 5 and 7 also have temperature differences that indicate that features in the experimental cell have a significant effect in the performance. These features are the reduction of the window size, more mass, or an intelligent controller. But it is the combination of these features that achieves the best performance.

4.2. Temperature difference ratio

The seven tests are also compared with each other using a ratio that we have called the TDR. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations (La Roche and Givoni, 2002). TDR can be calculated using the following equation:

Table 2
Average maximum temperatures

Series	Outdoor	Experimental cell	Control cell	Outdoor minus experimental	Control minus experimental cell
1. Window 50%	22.9	22.0	23.4	0.9	1.4
2. Window eliminated	24.3	22.3	24.3	2	2.0
3. Window added controller activated	25.4	23.9	24.7	1.5	0.85
4. Window 50%	29.9	28.1	28.7	1.8	0.6
5. Window eliminated	27.0	23.4	25.6	3.6	2.2
6. Mass added	26.5	23.2	26.3	3.3	3.1
7. Window added 100%	30.7	27.8	29.6	2.9	1.8

$$TDR = (T_{\max\text{out}} - T_{\max\text{in}}) / (T_{\max\text{out}} - T_{\min\text{out}}) \quad (2)$$

where TDR = temperature difference ratio, $T_{\max\text{out}}$ = maximum temperature outside, $T_{\max\text{in}}$ is maximum temperature inside and $T_{\min\text{out}}$ is minimum temperature inside.

The numerator is the difference between the indoor maximum temperature and the outside maximum, and the denominator is the outdoor swing. In a naturally ventilated building the result of this division cannot be higher than 1.0 and can be expressed as a percentage. The higher the value of the TDR, the better the cooling performance of the system. A higher value indicates that there is a larger temperature difference between outdoors and indoors and there is more cooling.

For this equation to be descriptive of the building performance there has to be a correlation between the outdoor swing and the difference between the indoor and outdoor maximum temperatures (Figs. 10 and 11). Each point in Figs. 10 and 11 contains one day's data, comparing the difference between the indoor and outdoor maximum temperature with the outdoor diurnal temperature swing. With both fixed and smart ventilation, as the swing increases, the difference between the indoor and outdoor maximums also increases. Fig. 10 shows data for each day of series 1 and 2, which have a fixed infiltration rate, and Fig. 11 shows the data for the next five series which use the smart controller. A separate trend line is plotted for each series, because each has different configurations. In all of them TDR increases as the swing increases.

The TDR concept normalises the capacity to reduce the indoor maximum temperature, which in this case is defined by differences in window sizes and mass, as a function of the outdoor swing, permitting comparing the different series with each other.

TDR is calculated for the different series and averaged for the days in each series with maximum outdoor

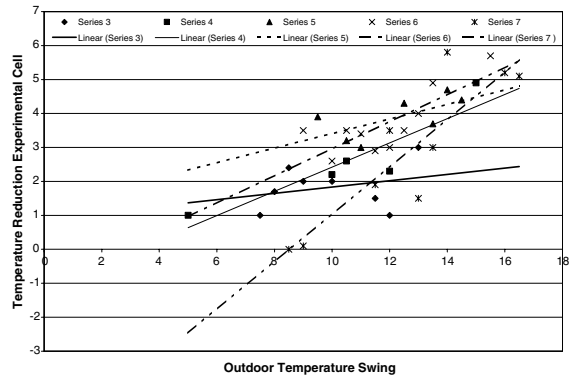


Fig. 11. Correlation between the daily outdoor temperature swing and the daily TDR in the experimental cell. Series 3,4,5,6 and 7 (smart ventilation).

temperatures above 25.5 °C (78 °F). The best TDR in the experimental cell is in series 6, which performs seven times better than the control cell in the same series and twice as good as before eliminating the window and adding the mass (Fig. 12).

The TDR is twice as good when the window is eliminated (Table 3). This is true when there is a fixed infiltration rate (series 1 compared to series 2) and when the smart controller is operating (series 3 compared to series 5).

Eqs. (3) and (4) predict the TDR (Fig. 13) as a function of south facing window to floor ratio. Except for the 12.5% window to floor ratio in the fixed infiltration mode that has two values, one point for each percentage value of window size in each series is plotted. Each of these points is the average TDR for that percentage of window. To determine the predictive equation, each series has at least three values, which represent three window sizes. The r^2 value for Eq. (3) with three points is 0.96 and for Eq. (4) with four points is 0.99.

The predictive equation for the test cell with a fixed infiltration rate of 0.7 air changes per hour is:

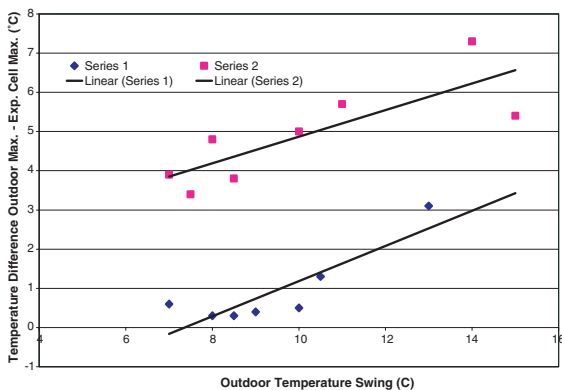


Fig. 10. Correlation between the daily outdoor temperature swing and the daily TDR in the experimental cell in series 1 and 2 (fixed infiltration).

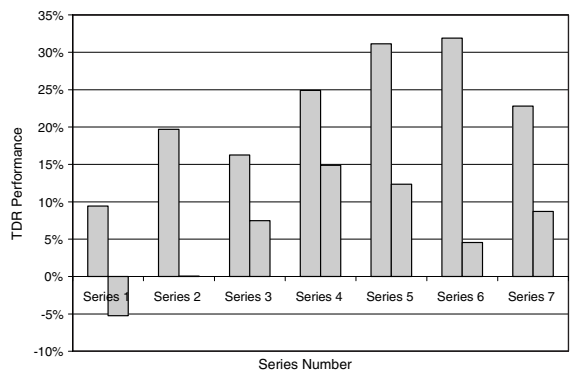


Fig. 12. TDR performance in the different series.

Table 3
Temperature difference ratio

Series	TDR experimental cell (%)	TDR control cell (%)	TDR experimental minus control cell
1. Window 50	9.4	-5.2	14.6
2. Window eliminated	19.7	0.1	19.6
3. Window added controller activated	24.9	14.9	10
4. Window 50%	16.3	7.5	8.8
5. Window eliminated	31.2	12.4	18.8
6. Mass added	31.9	4.5	27.4
7. Window added 100	22.8	8.7	14.1

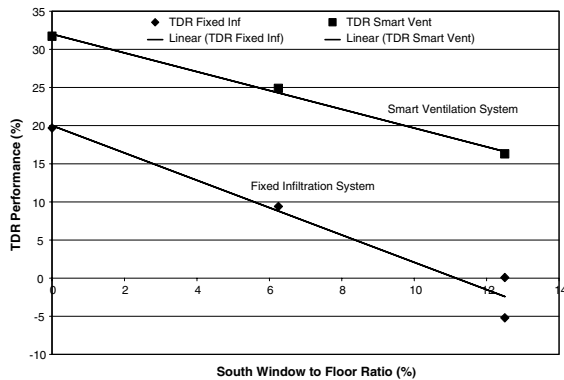


Fig. 13. Correlation between the south window to floor ratio and the TDR performance in the test cells with a fixed infiltration rate and a smart ventilation system, with standard mass.

$$\text{TDR} = 20 - 1.8 * \text{SWFR} \quad (3)$$

The predictive equation for the test cell with the smart ventilation system and a maximum ventilation rate of 3.9 air changes per hour is:

$$\text{TDR} = 32 - 1.2 * \text{SWFR} \quad (4)$$

In both, TDR = temperature difference ratio, SWFR = south window to floor ratio.

After TDR is calculated for a building using Eqs. (3) and (4), it is possible to predict the indoor maximum temperature using Eq. (2) and solving for T_{maxin}

$$T_{\text{maxin}} = T_{\text{maxout}} - [\text{TDR} * (T_{\text{maxout}} - T_{\text{minout}})]$$

where outdoor maximum and minimum temperatures, or daily temperature swing, must be known.

The two slopes for Eqs. (3) and (4) in Fig. 13 are similar. In both, as the south window to floor ratio increases, the TDR decreases. Larger south facing windows reduce the performance of a system that cools with ventilation. The slope for the smart ventilation system is about 12 TDR percentage points above the slope for the fixed controller system, indicating a better performance with the smart controller. When the south window to floor ratio is higher than 11.1% the conditions inside the

control cell, with a fixed infiltration rate, would be worse than outdoors while with the smart controller the south window to floor area can be up to 26.6% before indoor conditions inside temperature is higher than outside temperature. These equations could be used in buildings with lightweight walls, shaded north, east and west windows, and slab-on-grade construction to predict maximum temperatures with specific window sizes or to determine maximum window sizes that would achieve a specific performance.

4.3. Percentage of overheated hours and thermal comfort

The ASHRAE definition of comfort is “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE Handbook, 1997). Comfort is affected by several factors, generally classified as: (1) environmental: air temperature, air movement, humidity and radiation; (2) personal: metabolic rate, state of health and clothing; and (3) contributing: acclimatisation, body shape and subcutaneous fat. To define the comfort zone, many indices, developed from laboratory or field studies have been proposed. These are usually grouped in rational indices and adaptive indices, and there is debate as to whether there should be one or multiple indices to account for human adaptability (Nicol and Humphreys, 2002).

Of the variables that affect comfort, the most important, easy to understand and widely used is air temperature. Thus, even though comfort is not determined by air temperature alone, it is possible to obtain an idea of thermal comfort based on air temperature (Auliciems and Szokolay, 1997), especially when the other variables are not in extreme ranges as was the case in these series. For example relative humidity inside the cells during the daytime was usually between 45% and 65%. Ultimately, the success of a cooling strategy depends on the expectations of the occupants. Even though individuals that have some control over their environment and direct access to fresh air may adapt to conditions warmer than ASHRAE comfort standards (Scholar Brager and de Dear, 2000), and comfort indices vary if the building is free running or mechanically

cooled (DeDear and Brager, 1998), we have used a fixed comfort band between 21.1 and 25.5 °C (70–78 °F). These are the indoor design temperatures for heating and cooling as defined in the California Energy Code, Title 24, (1995). This comfort range is quite narrow and very conservative, but is thus also harder to comply with, better representing the expected comfort standards of Californians for whom this system is originally designed.

The number of hot, cold and comfortable hours and their distribution during the day permits the examination of the overall patterns inside the cell. The most important of these factors is the number of hot hours in each series because they negatively affect comfort in the summer and require the operation of the mechanical cooling system to lower temperatures to a comfortable level.

A matrix made up of 24 rows that represent each hour of the day and a number of columns equal to the number of measured days in a series is done. Each of these cells indicates the average temperature for each hour of each day and is color-coded to indicate if it is cool, comfortable or hot. If the value is below 70 °F the rectangle is shaded light gray, if it is between 70 and 78 °F it is medium gray, and if it is above 78 °F it is dark gray. The number of overheated hours for each series are indicated in Table 4 and the matrices for series 6, which is the best performing series, are presented (Figs. 14 and 15).

Series 1 and 2 do not have any overheated hours because outdoor temperatures were not over 25 °C. In the other series, there are always many more overheated hours in the control cell than in the experimental cell. The largest differences in the number of overheated

Table 4
Number and percentage of overheated hours in each series

Series	Number of overheated hours experimental cell	Percentage overheated hours experimental cell	Number of overheated hours control cell	Percentage overheated hours control cell
1. Window 50%	0	0	0	0
2. Window eliminated	0	0	0	0
3. Window added controller activated	0	0	4	2.5
4. Window 50%	28	26.1	52	48.6
5. Window eliminated	0	0	28	17.5
6. Mass added	3	1.8	30	17.8
7. Window added 100%	47	25	70	37.2

hour	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	15-Aug
1	20.4	20.5	20.5	21.2	21.8	20.9	19.7
2	19.9	20.2	20.1	20.9	21.4	20.5	19.4
3	19.5	19.8	19.9	20.5	21.1	20.2	19.2
4	19.1	19.6	19.6	20.2	20.8	20.0	19.0
5	18.7	19.2	19.4	19.9	20.3	19.7	18.9
6	18.3	18.8	19.1	19.6	20.0	19.5	18.7
7	18.1	18.7	19.0	19.5	19.8	19.6	18.5
8	18.5	19.0	19.4	19.9	20.0	19.4	18.3
9	19.5	19.8	20.3	20.8	20.7	19.9	18.5
10	20.9	21.0	21.6	22.0	21.6	20.8	18.8
11	22.5	22.2	22.6	23.0	22.7	21.5	19.6
12	24.0	23.3	23.6	24.0	23.7	22.3	20.7
13	24.3	24.0	24.2	25.0	24.5	23.1	21.8
14	24.6	24.4	24.7	25.7	25.1	23.9	22.5
15	24.8	24.7	25.1	25.9	25.4	24.0	23.0
16	24.8	24.8	25.5	26.1	25.5	23.9	23.1
17	24.8	24.9	25.5	26.1	25.6	23.4	23.0
18	24.6	24.2	25.3	25.9	25.3	22.8	22.5
19	23.7	23.2	24.9	25.4	24.7	22.2	21.8
20	23.1	22.8	23.6	24.5	23.6	21.6	21.3
21	22.4	22.3	22.9	23.5	22.8	21.1	20.8
22	21.9	21.8	22.4	23.1	22.2	20.7	20.3
23	21.3	21.3	22.0	22.6	21.8	20.4	19.9
24	21.0	20.8	21.5	22.2	21.3	20.0	19.6

Fig. 14. Hot, comfortable and cool hours in the experimental cell for seven days in series 6.

hour	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	15-Aug
1	21.6	22.3	22.2	23.0	23.5	22.5	21.4
2	21.1	21.9	21.8	22.6	23.0	22.1	21.1
3	20.7	21.4	21.5	22.1	22.6	21.7	20.8
4	20.2	21.1	21.2	21.8	22.2	21.5	20.6
5	19.8	20.6	20.8	21.4	21.8	21.2	20.4
6	19.3	20.2	20.5	21.1	21.4	20.8	20.2
7	19.1	19.9	20.4	20.9	21.1	20.5	19.9
8	19.5	20.2	20.6	21.2	21.4	20.7	19.7
9	20.6	21.2	21.7	22.2	21.9	21.3	19.8
10	22.5	22.6	23.2	23.6	23.0	22.2	20.3
11	24.6	24.3	24.6	24.9	24.7	23.2	21.5
12	26.5	25.7	25.9	26.3	25.9	24.4	23.2
13	27.0	26.6	26.7	27.9	27.0	25.8	24.6
14	27.5	27.3	27.5	29.0	28.0	26.7	25.7
15	27.9	27.8	28.2	29.4	28.6	27.2	26.4
16	28.0	28.0	28.8	29.5	28.8	27.4	26.6
17	27.8	28.0	28.8	29.5	28.8	26.8	26.4
18	27.4	27.5	28.1	28.9	28.1	26.1	25.9
19	26.9	26.7	27.4	27.9	27.2	25.2	25.0
20	25.9	25.6	26.3	26.7	25.9	24.0	23.9
21	24.8	24.6	25.3	25.7	25.0	23.2	23.1
22	24.0	23.8	24.6	25.1	24.2	22.7	22.5
23	23.2	23.2	24.0	24.5	23.5	22.3	22.0
24	22.7	22.6	23.4	24.0	23.0	21.9	21.6

Fig. 15. Hot, comfortable and cool hours in the control cell in series 6.

hours are in series 5 and 6, which have no window and more mass.

This matrix indicates how the test cells perform on an hourly basis during the whole measurement period and permits a visual comparison of their performance. Of the total hours in the experimental series, three hours (1.8%) are overheated, while 30 h (17.8%) in the control cell are overheated. This is a difference of ten times between the cells. Thus, even though the difference between the maximum temperatures in the two cells is 3.1 °C there is an appreciable difference in the number of overheated hours.

5. Conclusions

This paper demonstrates that it is possible to use smart controllers to cool a test cell in Los Angeles. The factors that affect the performance of this system are the air change rate, the value of comfort low, the thermal capacity of the building and solar gains through the windows.

A higher air change rate during the cooling period increases the amount of heat that is flushed out of the building, lowering the temperature of the mass, and lowering the maximum temperature for the next day. The test cells that had the smart ventilation system, and could increase the air change rate when needed, always performed better than the test cells with a fixed infiltration rate. The system performed better with maximum air change rates of 15 air changes/hour instead of 4

air changes/hour, but satisfactory results were achieved with maximum air change rates of only 4 air changes/hour, probably because of the limited amount of mass inside the test cells.

The value of comfort low determines the lowest temperature that will be achieved inside the building at night. After the indoor air temperature is cooled to this value, the damper is closed and the indoor air temperature is maintained, even though the outdoor temperature could descend below this point. If the value of comfort low is reduced, the indoor maximum temperature of the building the next day is also reduced. To achieve maximum cooling the next day, the value of comfort low should be set to the minimum temperature that can be tolerated at night. 18.33 °C was used in the seven series detailed in this paper, and daytime performance would improve if this value was lower.

The amount of mass inside the building affects the thermal inertia so that the cooling effect, which is mostly at night, can be translated to the next day, reducing the maximum temperatures inside the building. Two amounts of mass were tested using the smart controller. With a slab on grade building as defined by the California energy code, the difference between the control and the experimental cell is 2.2 °C. When more mass is added to the experimental test cell the temperature difference increases to 3.1 °C. The best TDR ratio is also with the additional mass. Even with additional mass, the rate of 3.9 air changes per hour seemed sufficient to cool the mass to the comfort low value of 18.33 °C.

Solar radiation is an important factor that reduces the performance of the cooling system if it is not controlled. In all the series and with all indicators an increase in the unprotected window size was followed by a decrease in the performance of the system. The performance is inversely proportional to window size, and performance is also consistently better when the smart ventilation system is used instead of the fixed infiltration.

These results can be extrapolated to slab-on-grade houses that meet the California Energy Code. The maximum indoor temperatures inside these buildings can be predicted using a two step process in which we must calculate the TDR as a function of the south facing window to floor ratio and determine the maximum temperature using Eq. (2).

In all cases comfort is improved by more mass, smart ventilation controllers or smaller windows. Even though the systems with the “no window” case exhibit the best performance, windows are important sources of natural light and views in buildings, so they obviously must not be completely eliminated. South facing windows are also important assets for winter heating in mild mid-latitude climates. Shading systems should be designed to block solar radiation from these windows in the summer and increase the cooling performance of the system.

This smart controller that we have designed has the additional advantage of being able to adjust the ventilation rate as needed in the building, and when cool enough temperatures are available outdoors. The hours in which the air change rate must be reduced or increased vary from day to day and the system sometimes turns on during the day if conditions are favorable. A smart controller provides additional cooling as compared to traditional systems that have fixed operating times, because it knows when it will be effective to cool with outdoor air. This improves the performance of the cooling system reducing the amount of mass needed. Furthermore, the cooling system maintains the indoor temperatures inside the comfort band, reducing the number of overheated hours as compared to the control cell. The system keeps the indoor air temperature inside the comfort zone by using outside air to cool whenever it is possible, and using the thermal inertia of the mass to “coast” during the warmer hours of the day.

Since comfort low and comfort high in the system are also adjustable by the user, the user has control over his environment and the system can be tailored to individual requirements, increasing the controller’s performance even more. Unfortunately, as yet there is no residential thermostat available on the market like the controller used in these tests. However it would be a simple matter to add a thermistor to read outdoor temperature and to modify the microprocessor of a thermostat to implement these rules in a smart thermostat. It is hoped that these resources will inspire

manufacturers to expand their product lines to offer these capabilities.

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