EFFECTS OF COMBINING SMART SHADING AND VENTILATION ON THERMAL COMFORT

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ABSTRACT

A prototype microcomputer-controlled thermostat that can operate different systems in a building according to comfort requirements and resources in the environment has been developed by the authors. This intelligent control system has been tested measuring indoor and outdoor temperature to operate a fan and/or blinds.

This paper presents some results of a study done in the summer of 2004, comparing the performance of the test cell operating with both the fan and shades with previous series in the summers of 2002 and 2003 with only either the fan or the shade operating. All of them were also compared to a reference cell without shades or fans. Other variables, such as the amount of mass and insulation levels are fixed in all series.

Results indicate that in this climate all of these strategies help to achieve more comfortable conditions inside the experimental cell than the control cell but that some perform better than others. A higher air change works better than a lower air change, and shade outside works better than shade inside, but when both shade outside and increased air changes were combined, there was no noticeable improvement in the performance of the test cell.

1. INTRODUCTION

Night flushing 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. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Night ventilation reduces internal maximum temperatures, peak cooling loads, and overall energy consumption.

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 for nocturnal ventilative cooling to be effective.

In previous papers a smart controller that optimizes the use of forced ventilation for structure cooling in a building was tested (1) (2). This controller uses a set of decision rules to control a fan to maximize indoor thermal comfort and minimize cooling energy costs using outdoor air, a great source of free cooling energy. 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, reducing the need for air conditioning.

The ability of this smart system to cool with natural ventilation can be seriously compromised if certain design considerations are not taken into account regarding the amount of mass and the control of solar radiation. This was also documented in previous papers (2) (3) (4).

There are also several climatic parameters that determine the effectiveness of nocturnal ventilative cooling: the minimum air temperature, daily temperature swing, and water vapor pressure level (5).

A smart system that reduces both the heat load through windows, while increasing the night cooling by ventilation, should be more efficient that one that controls only one of these. This paper discusses the effect of both smart ventilation and smart shading on indoor temperature compared to only smart ventilation or smart shading .

2. EXPERIMENTAL SYSTEM

The experimental system has been described in detail in other papers (4). It consists of a microprocessor controller connected to thermistors that measure temperature, a computer (datalogger) which contains the control programs and collects and stores experimental data, the two test cells with an active ventilation system, shading system or both (Figures 1) The test cells are identical and built icluding the characteristics of typical California slab-on-grade houses that could affect the thermal performance of the ventilation system: the insulation level, the brick slab and the glazing. Another simplification was that both cells only had a south-facing window so that they would receive the same amount of radiation simultaneously.

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 center of the cell, but at different heights. The lowest one is 5 cm (2 in) above the bricks, the middle one is 137 cm (54 in) and the highest one is 231 cm (91in), which is 10 cm below the ceiling. In the experimental cell an additional thermistor measures the temperature of the mass. Only air temperature at a height of 137 cm is reported in this paper.

One of these cells is the "experimental" cell, which has either the smart shading system, the smart venting system or both. The other cell is the "control" cell with a fixed infiltration rate and no shading on the window.

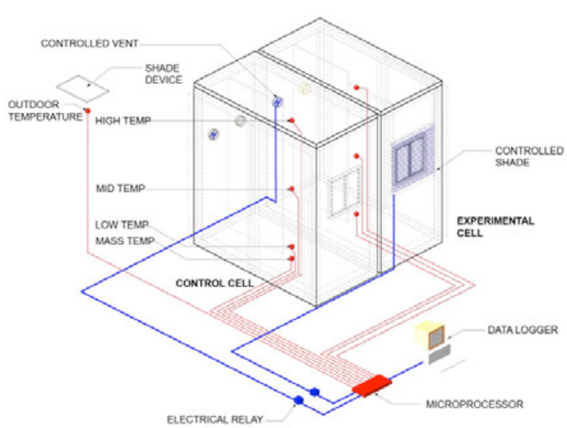

Fig. 1: The experimental system with controlled shading and controlled ventilation

Fig. 2: The experimental and control cells viewed from the south with the shade system and without the shade system

Various control strategies were tested in the summer of 2001 comparing the effect of different air change rates and the values for comfort low and comfort high (1). The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell (equation 1) and was used for all of the series in which smart ventilation is used in this paper.

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* fan ON else fan OFF [Eq. 1]

Where:
t_o = temperature outside
t_i =temperature inside
C_{f_low}, = comfort low at 18.33 °C (65 °F)
C_{f_high} = Comfort high at 25.55 °C (78 °F).

The rule that is used for smart shading was developed and tested in 2003 (3) and is:

If 70 F < t_i *then* Shade Down else Shade Up. [Eq. 02]

3. EXPERIMENTAL RESULTS

Six series, between 2001 and 2004, that compare the performance of the test cell operating with smart shades only, smart ventilation only, and both smart ventilation and smart shade fan are presented (Table 1). Even though the system was also tested for heating, only the summer performance is presented in this paper. All of the series were also compared to an unshaded reference case without the smart ventilation or shading system. The amount of mass and the insulation levels are the same in all series.

TABLE 1: SERIES ANALYZED IN THIS PAPER

Series Number & Name	Date	Venting System	Shade System
Series 1: Shade Inside & Fan off	Aug 2 (2003)	OFF	ON
Series 2: Shade outside & Fan off	Aug 27 (2003)	OFF	ON
Series 3: Shade Off & Fan on low	Sep 24 (2001)	ON Up to 3.9 air changes/hour	OFF
Series 4: Shade off & Fan on high	Aug 30 (2001)	ON Up to 15 air changes/hour	OFF
Series 5: Shade inside & Fan on high	Sep 11 (2004)	ON Up to 15 air changes/hour	ON
Series 6: Shade outside & fan on high	July 9 (2004)	ON Up to 15 air changes/hour	ON

3.1. Series 1: Shade inside and Fan Off

The blinds are on the inside face of the window (interior of the test cell) and the ventilation system is turned off, allowing only basic infiltration, for a minimal air change rate (Fig 2).

The values of the control and experimental cell are close together most of the time.

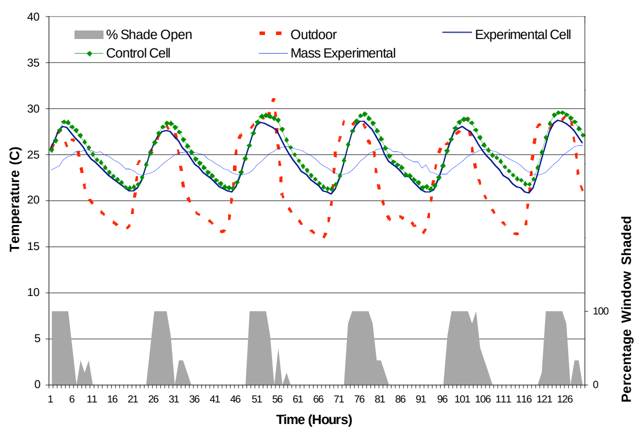

Fig. 2: Series 1, shade inside and fan off

3.2. Series 2: Shade Outside and fan off

The blinds are on the outside face of the window (exterior of the test cell) and the ventilation system is off, allowing basic infiltration for a minimal air change rate (Fig 3).

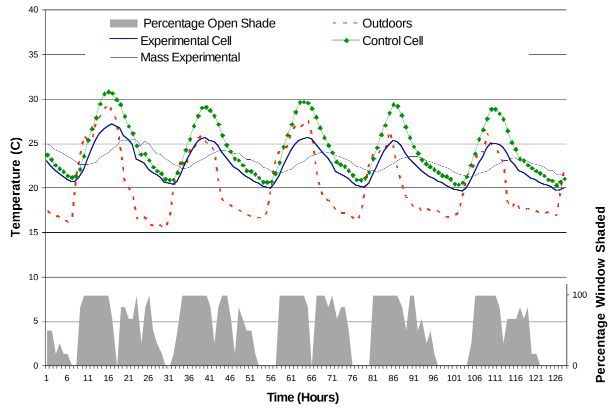

Fig. 3: Series 2, shade outside and fan off

3.3. Series 3: Shade off and fan on

The window is unshaded, and the ventilation system is turned on, with an air change rate that goes up to 3.9 air changes/hour. Comfort low is 65 °F and comfort high is 78 °F (18.3 to 25.5ºC) (Fig 4).

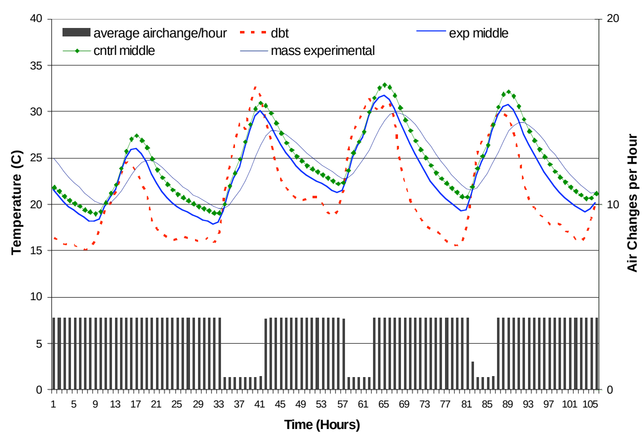

Fig. 4: Series 3, no shade and fan on

3.4. Series 4, Shade Off and Fan On with more air changes/hour

The same set of rules as in the previous series are applied, but the maximum air change rate is increased to 15 air changes per hour (Fig 5).

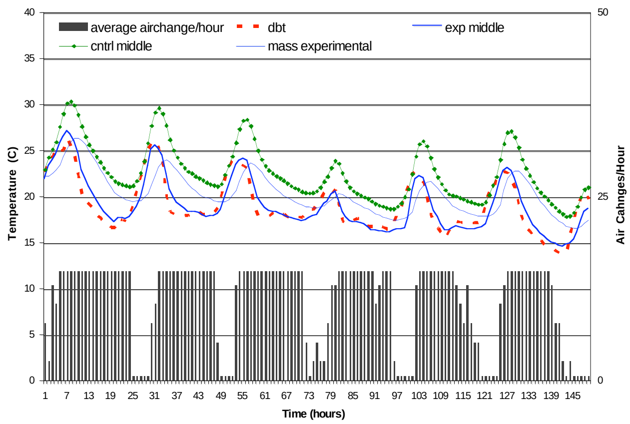

Fig. 5: Series 4, no shade and fan on with more air changes

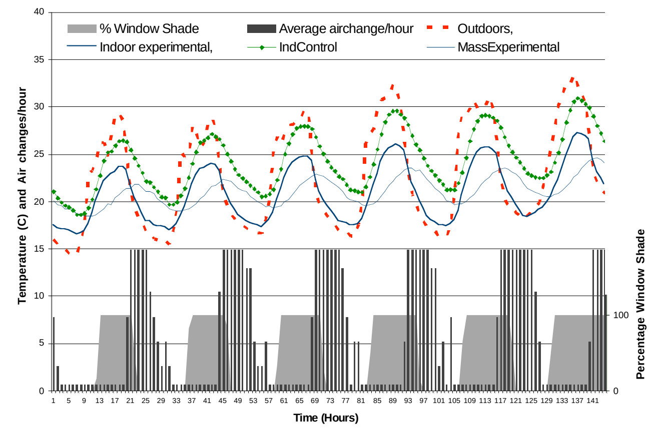

Fig. 7: Series 6, shade on and outside and fan on with more air changes

3.5. Series 5, Shade operating inside and fan on

The maximum air change and infiltration are the same as in the previous series, and the shade system is also operating with the blinds on the inside of the cell (Fig 6).

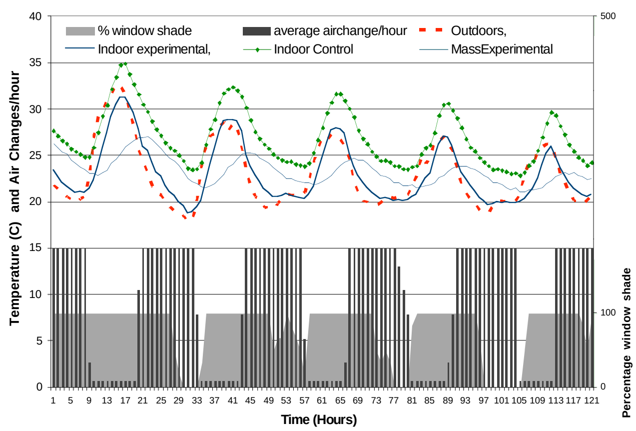

Fig. 6: Series 5, shade on and inside and fan on with more air changes

3.6. Series 6. Shade operating outside and fan on

The maximum air change is the same as in the previous series, while the shade system is also operating with the blinds on the outside of the cell (Fig 7).

4. DISCUSSION

Two variables were used to compare the series, the difference in the average maximum temperature between the experimental and control cells and the number of overheated hours as a ratio between both cells.

4.1. Differences of the Maximum Average Temperatures

The difference between the average maximum temperatures in the two cells is indicative of the performance of the system. The lower the average maximum temperature and the larger the difference between the maximum averages in both cells, the better the performance of the experimental cell (Table 2). In all of the series the experimental test cell always has a lower average maximum temperature than the control cell and equal to or lower than the outdoors.

TABLE 2: MAXIMUM AVERAGE TEMPERATURE

	Experimental Cell	**Outside**	**Control Cell**	**Experimental minus control**
Series 1:	28.2	29.0	29.5	-1.3
Series 2:	26.0	27.6	29.9	-3.9
Series 3:	30.8	31.4	32.0	-1.2
Series 4:	23.8	23.8	27.6	-3.8
Series 5:	28.1	28.4	31.8	-3.7
Series 6:	25.2	30.8	28.5	-3.3

There are four series in which the difference in the maximum average temperatures in the experimental cell and the control cell is significant, above 3 C (Fig 8). In these there are features in the experimental cell that have a significant positive effect in their performance. These features are the shade operating outside, the fan operating with more air changes per hour, both fan and shade operating with the shade inside, and both fan and shade operating with the shade outside.

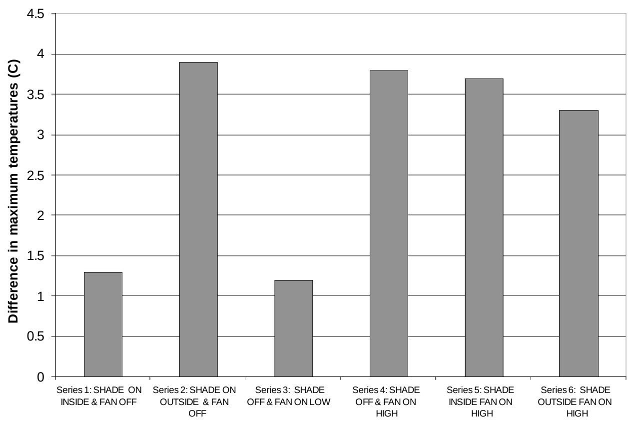

Fig. 8: Differences in the average maximum temperatures (Experimental minus control) for each series

4.2. <u>Comparison of the Hours in Comfort</u>

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 (6), especially when the other variables are not in extreme ranges as was the case in these series. Relative humidity inside the cells during the daytime was usually between 45% and 65%. We have used a fixed comfort band between 21.1 °C and 25.5 °C (70-78 °F), which 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 thus harder to comply with, better representing the expected comfort standards of Californians for whom this system was 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 is the number of hot hours series because they would 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 for the two cells and outdoors. This matrix indicates the hourly performance of the test cells during the measurement period, permitting a comparison of their performance (Table 3). The matrix for the experimental and control cells in series 5 are presented as an example matrix. The darker cells show the pattern for the overheated hours, the control cell is on the left side and the experimental cell on the right side.

	11-Sep	12-Sep	13-Sep	14-Sep	15-Sep	hour	11-Sep	12-Sep	13-Sep	14-Sep	15-Sep
1	23.2	22.2	20.7	20.6	20.3	1	23.3	22.7	21.0	20.6	20.0
2	22.7	21.3	20.5	20.6	20.1	2	22.7	21.8	20.5	20.3	19.6
3	22.1	20.7	20.7	21.0	20.2	3	22.0	21.1	20.5	20.4	19.7
4	21.7	20.5	21.0	20.9	20.5	4	21.6	20.6	20.6	20.3	19.9
5	21.2	20.2	21.2	20.6	20.4	5	21.2	19.9	20.8	20.1	19.9
6	20.9	19.8	21.2	20.7	20.5	6	20.9	19.5	20.6	20.1	20.0
7	21.0	19.1	21.0	20.6	20.2	7	21.0	18.7	20.5	20.0	19.9
8	21.3	19.2	21.0	20.8	20.4	8	21.0	18.8	20.4	20.1	19.8
9	22.5	20.2	21.2	21.9	20.8	9	21.4	19.5	20.2	20.5	19.9
10	24.8	22.2	23.0	22.9	22.2	10	22.2	20.1	20.7	20.7	20.3
11	28.1	26.3	26.0	25.7	23.5	11	23.8	21.9	21.6	21.7	20.9
12	31.2	30.5	30.3	26.3	24.7	12	25.8	24.0	23.1	22.5	21.3
13	40.2	39.0	37.8	30.4	31.6	13	27.3	25.6	24.6	23.0	22.5
14	45.7	44.7	42.8	39.8	38.1	14	29.1	27.6	26.4	24.7	23.9
15	46.8	40.1	44.0	42.1	39.8	15	30.4	28.7	27.7	26.1	25.2
16	42.5	38.4	39.6	38.6	37.2	16	31.2	28.8	27.9	27.0	26.0
17	37.2	34.8	34.0	33.0	29.1	17	31.2	28.8	27.8	26.9	24.9
18	34.0	32.4	31.1	29.9	25.5	18	30.5	28.7	27.3	26.0	23.6
19	30.7	28.9	26.7	25.8	23.9	19	29.5	27.5	25.2	24.3	22.9
20	28.0	25.4	24.1	23.4	22.3	20	27.8	25.1	23.8	23.1	22.1
21	25.9	23.6	22.7	22.3	21.5	21	25.9	23.8	22.8	22.3	21.4
22	25.3	22.6	21.9	21.6	21.1	22	25.5	22.8	22.0	21.7	21.1
23	24.0	21.9	21.4	21.0	20.8	23	24.2	22.2	21.5	21.1	20.7
24	22.9	21.1	20.7	20.4	20.8	24	23.2	21.4	20.9	20.4	20.5

Fig. 9: Experimental cell on the right and control cell on the left for series 5, Cool, comfortable and overheated hours.

<u>TABLE 3: PERCENTAGE OVERHEATED HOURS</u>

Series Number & Name	% Overheated Hours			
	Out.	Exp.	Cont.	Ratio of Control to Exp.
Series 1: Shade In & Fan Off	46.7	65.8	75.0	88%
Series 2: Shade Out & Fan Off	13.3	7.5	31.7	24%
Series 3: Shade Off & Fan Low	1.7	20.8	28.3	73%
Series 4: Shade Off & Fan High	1.5	0.5	14.2	4%
Series 5: Shade In & Fan High	30	22.5	36.7	61%
Series 6: Shade Out & Fan High	39.6	7.6	14.6	52%

Figure 10 presents the percentage of overheated hours in the control and experimental cells and figure 11 presents the ratio of overheated hours in the experimental cell compared to the control cell. The lower the ratio, the better the performance of the experimental cell. Comparison of the ratios indicates that series 2 and 4 are the best performing series. The shade is outside in the first case and the fan on high in the second case. Combining the fan with the shade either outside or inside (series 5 and 6) works almost as well as these two (series 2 and 4). Fan on low and the shade inside by themselves have the worse performance.

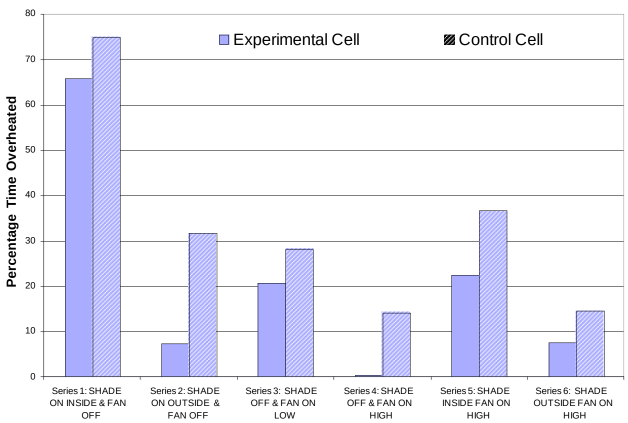

Figure 10: Percentage of Overheated Hours in Control Cell to Experimental Cell

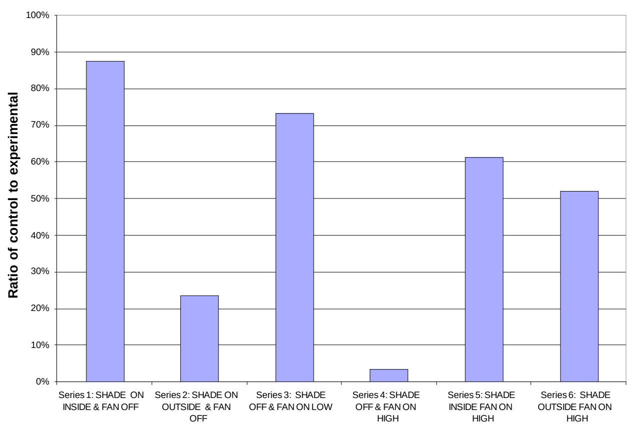

Figure 11: Ratio of Overheated Hours in Control Cell to Experimental Cell

5. CONCLUSIONS

This paper demonstrates that it is possible to use smart controllers with ventilation and/or shade systems to cool a test cell in Los Angeles. In all cases comfort is improved by the smart ventilation system, the smart shading system or both. These do a good job of maintaining the indoor temperatures inside the comfort band, reducing the number of overheated hours and the maximum temperature inside the experimental test cells.

The features that worked best in these series were when the shade system is on the outside of the test cell and when the air change rate is increased to 15 air changes/hour. When smart shading, either outside or inside was combined with smart ventilation there was no noticeable improvement compared to the previous two cases that only had external shades or a higher air change rate. Smart ventilation with a lower air change rate and smart shading on the inside by themselves had the worst performance.

Surprisingly, combining smart ventilation at higher air changes with smart shading on the outside of the window did not improve the cooling performance of the test cells when compared to either of these strategies by themselves. When higher air changes was combined with the shading inside of the window, the overall performance of the system did improve.

6. ACKNOWLEDGEMENTS

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