EFFECTS OF THERMAL PARAMETERS ON THE PERFORMANCE OF AN INTELLIGENT CONTROLLER FOR VENTILATION

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ABSTRACT

To increase the application of nocturnal ventilative cooling (night flushing) and daytime comfort ventilation an intelligent control system has been designed that manages air flow according to cooling needs in a building and resources in the environment. This system is a microcomputer-controlled thermostat with both indoor and outdoor temperature sensors that can control a whole-house fan, in addition to the furnace and air conditioner. No such thermostat is currently available commercially. The rules for various control strategies have been programmed and tested using two slab floor test cells. It has proven effective in reducing both the maximum temperature and the number of overheated hours in the test cell, compared to the control cell. An "optimum" series was tested experimentally and modeled with the HEED computer program in different California climate zones demonstrating potential savings for ratepayers.

1. INTRODUCTION

This project demonstrated the feasibility of a new kind of intelligent ventilation controller that can minimize cooling energy costs for California homeowners.

The greatest potential source of FREE cooling energy in most California climates is outdoor air. Typically in much of California, summer daytime temperatures are too hot but night temperatures are quite comfortable. This controller knows how much night-time air should be brought in to cool down the building's interior mass so that it can 'coast' comfortably through the next day. The need for air conditioning can be greatly reduced or even eliminated, particularly if the home is carefully designed to prevent excess solar gains or infiltration. Experiments showed that this controller always reduced the peak indoor temperatures and the number of overheated hours.

This controller is similar to a conventional programmable thermostat, but with the addition of an outdoor temperature sensor and a microprocessor to hold the expanded control logic. The house needs to have a whole-house exhaust fan and a strategy for operating windows or air inlets, and as much internal mass as possible but at least a slab floor. No such controller is on the market today.

2. EXPERIMENTAL SYSTEM

The experimental system consists of a Controller-Processor with thermistors to measure temperature, a Laptop computer connected to the Microcomputer 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-inch inlet and on the outlet side a four-inch constantly running fan and a reducer to match the diameter of the anemometer. The inlet damper is opened and closed in the experimental cell by a signal from the microcomputer, and the damper is fixed in the closed position on the control cell. The "closed" position is actually open slightly to allow the same controlled amount of infiltration in each cell. The tests and system are explained in more detail in (1) and (2).

Two identical test cells were built simulating the characteristics of typical California slab-on grade houses. They are 4 ft wide by 8 ft long and 8 ft high and are oriented with the longest facade towards the east and west. The cells have 3" foam R12 insulation on the outside and ¼" gypsum inside the walls and roofs. The floor is hardboard placed on top of an insulation panel and the roof has two layers of insulation, one on top of each other for R24. There is a 2 x 2 ft (4 f^2) double pane window on the south side with a Solar Heat Gain Coefficient of 0.72 and a U value of 0.75. The ratio of the glazing to floor area is 12.5 %. The east and west walls are shaded by another layer of insulation separated by about 3 inches from the wall, to generate an air chamber in between the two layers and block the influence of morning and afternoon sun. The walls and windows are carefully sealed so that infiltration is controlled only by the fan and damper system.

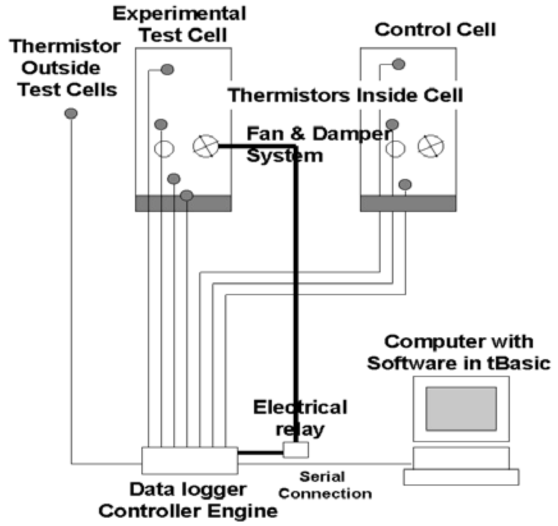

Fig. 1: The Experimental System

In all of the tests, each cell has 106 cement bricks distributed evenly in the floor simulating a concrete slab. The bricks are 4” x 8” x 2.5” and are spread evenly over the surface of the floor.

The flow rate is adjusted to 13.21 cfm when the damper is open in the experimental cell and 2.4 cfm when the damper is closed. Since the internal volume of the cells is 202.4 cubic feet, this is equivalent to 3.9 air changes per hour when the damper open and 0.7 air changes when it is closed, representing infiltration. In the control cell the damper is kept closed with a fixed airflow rate of 2.4 cfm (0.7 air changes per hour). Another series is performed with a maximum air change rate of 15-air changes hour in the experimental cell and an indeterminate minimum air change rate close to 0.5 air changes per hour. With a high capacity whole house fan, up to 30 air changes per hour can be achieved.

The objective of all the controller programs is to use the air to achieve comfort with minimum energy consumption. Since both cells are built identically, performance can be evaluated by comparing the results of the experimental cell with the control cell.

Fig. 2: The Test Cells

The controller programs are simple enough so that they can be built into a thermostat and any homeowner can understand them:

- If the indoor temperature is higher than the outdoor temperature the airflow rate should increase (damper open) so that a larger amount of cool air enters the building. If the indoor temperature is higher than the outside temperature, the airflow rate should be reduced (damper “closed”) so that the warmer outside air does not enter the building. This rule can be combined with one or both of the following additional rules.
- If the air temperature is below a given minimum value the airflow rate should be reduced to avoid overcooling of the building. This value is called comfort low because it is a comfort control for low temperatures.
- If the air temperature is above a given maximum value the damper will close to avoid overheating of the building by ventilation. This option can be linked to a mechanical cooling system (air conditioner) so that if the indoor temperature is above this comfort level the mechanical cooling system is activated.

These control strategies can be grouped together in different configurations and using different values for comfort low and comfort high, which can be adjusted by the user. Traditional ventilation systems are based on simpler fixed options, such as predefined hours or only the value of the internal temperatures.

3. EXPERIMENTAL RESULTS

Several tests were performed in the summer of 2000 and 2001 and five of them are presented in this paper. Analysis helps determine the most effective rules.

TABLE 1: TESTS PRESENTED IN THIS PAPER

Series	Comf Low (°C)	Comf High (°C)	Min Air Changes/ Hour	Max Air Changes / Hour
Basic Comfort	21.1	25.5	0.7	3.9
Reduced Comfort Low	18.3	25.5	0.7	3.9
Reads Mass Temperature	21.1	25.5	0.7	3.9
Increased air change rate	21.1	none	uncontrolled	15
Higher air change rate & lower cmf low	15.6	none	uncontrolled	15

3.1 Series 1: Basic Comfort Zone Configuration

This first test is set so that the system will shut off whenever conditions are outside the conventional comfort zone, of 21.1 and 25.5 °C (70-78 °F). The fan controller mechanism is programmed to increase the air change rate to 3.9 air changes/ hour according to the following rule:

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* activate fan

t_{o}: Temperature outside
t_{i}: Temperature inside
C_{f_low}: Comfort low = 21.1 °C
C_{f_high}: Comfort high = 25.5 °C

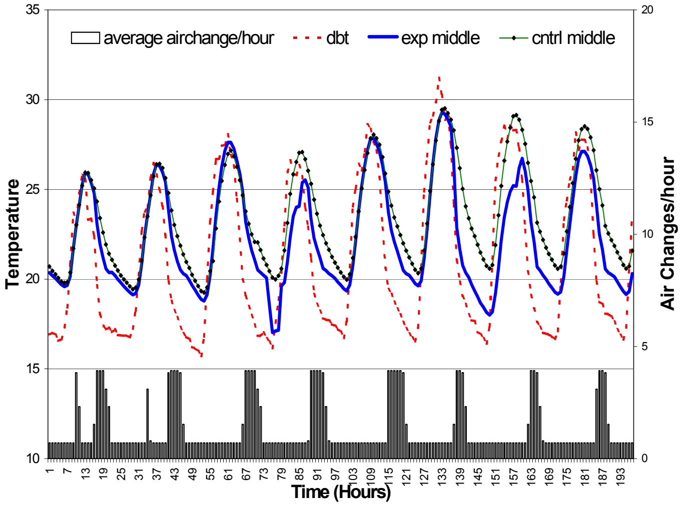

Figure 3: Series 1, Basic Comfort Zone Configuration.

3.2 Series 2: Reduced Comfort Low

The same rules are used but comfort low is reduced to 18.33 °C (65 °F) to increase the heat sink capacity of the mass.

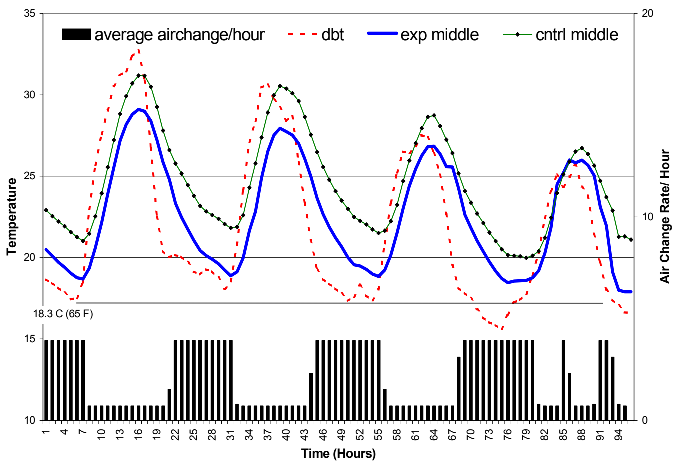

Fig. 4: Series 2, Reduced Comfort Low.

3.3 Series 3: Coupled to Mass temperature

The operation of the cooling system is determined by the relationship of the outside air temperature with the mass temperature inside the building, which is the actual storage medium of the energy not indoor air temperature. The mass temperature probe is located in between two bricks about one inch from the surface. The airflow rate is increased when the outdoor temperature is lower than the mass temperature, while the air temperature is used as a comfort control, shutting off the system whenever the indoor temperature is above or below the comfort zone. Comfort low is set at 21.1 °C (70 °F) and comfort high at 25.2 °C (78 °F). Mass temperature is an indicator of the amount of heat that can be stored, while the air temperature regulates comfort. When the indoor air temperature reaches the maximum comfort value, natural ventilation will be reduced and an optional mechanical cooling system can be activated to maintain comfort using only the venting system. The rule is in the following form:

If $t_{to} < t_{mass}$ and $t_i > C_{cf\_low\ and}$ $t_i < C_{cf\_high}$ *then* activate fan

t_{o}: Temperature outside
t_{mass}: Temperature of the mass inside the test cell
C_{f_low}: Comfort low
C_{f_high}: Comfort high

3.4 Series 4: Increased Air Change Rate

The same set of rules as in series 3 are applied, but the maximum air change rate is increased to 15 air changes / hour, while the infiltration air change rate is around 0.5 air changes / hour but is not determined.

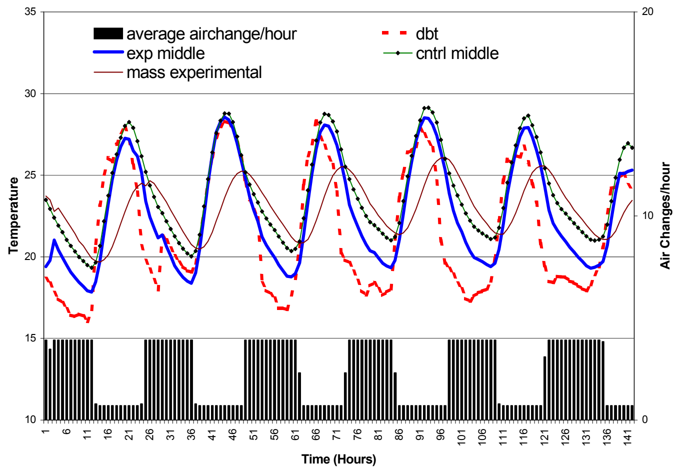

Fig. 5: Series 3, Coupled to Mass Temperature

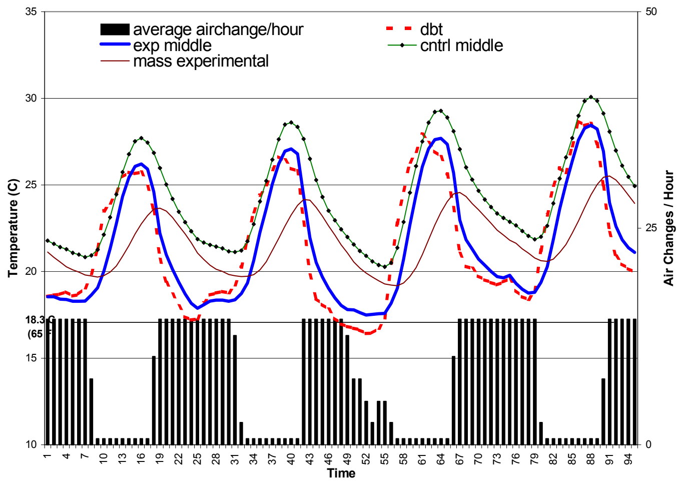

Fig. 6: Series 4, Increased Air Change Rate

3.5 Series 5: Higher air Change Rate & Lower Comfort low

The maximum air change rate is again increased to 15 air changes/hour and the minimum is undetermined. Comfort low is set at 15.66 °C and there is no upper comfort limit. The rule for this series is in the following form:

If $t_{to} < t_i$ and $t_i > C_{cf\_low}$ *then* increase air change rate

t_o: Temperature outside

t_i: Temperature of the air inside the test cell

C_{f_low}: Comfort low

4. RESULTS

The number of hot hours and the reduction of the maximum temperature are used to evaluate the performance of the different series. The first value is expressed as a percentage of the total number of hours in the series and the reduction of the maximum temperature, when compared to the swing permits to determine the performance of the series and compare both cells.

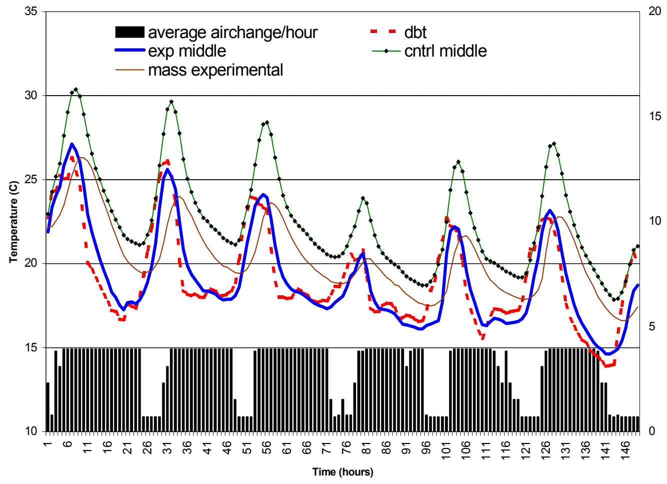

Fig. 7: Series 5, Higher Air Change Rate & Reduced Comfort Low

4.2.1 Percentage of Hot Hours & Performance

The percentage of hot hours in the experimental cell is compared with the control cell. 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 the series is done for each series. Each of these cells indicates the temperature of one hour for each day. If the value is below 70 °F the rectangle is colored light gray, if it is between 70 and 78 °F it is shaded medium gray, and if it is above 78 °F it is shaded dark gray. These figures are not shown for lack of space, but in table 2 the percentage of hot hours for each series is presented. The factors that are most important for the performance of a ventilation system are the increased air change rate, and reduced comfort low.

TABLE 2: HOT HOURS OUTDOORS IN THE EXPERIMENTAL AND CONTROL CELLS.

	Outdoor	Control	Exp	Cnt - Exp
S 1	27.6	24.5	18.8	5.7
S 2	21.7	32.5	15	17.5
S 3	21.5	32.6	23.6	9
S 4	14.8	24.4	14.8	9.6
S 5	3.1	12.7	0	12.7

TABLE 3: PERFORMANCE OF THE DIFFERENT SERIES ADJUSTED FOR DAYS WITH MAXIMUM TEMPERATURES ABOVE 25 °C.

Series	Performance Experimental	Performance Control	Numerical Improvement over Control
S 1	7.30%	0.46%	6.84%
S 2	13.93%	-0.82%	14.75%
S 3	3.56%	-10.01%	13.57%
S 4	-1.08%	-17.2%	16.13%
S 5	-3.3%	-23.1%	19.8%

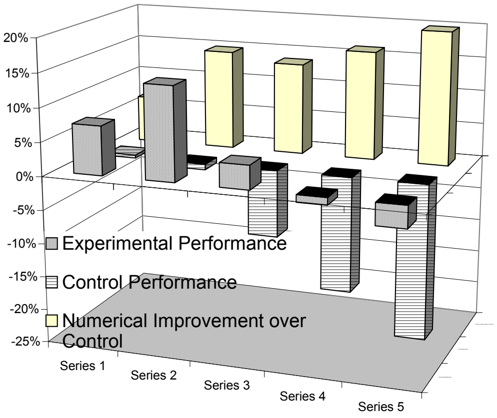

Fig. 8: Performance of the Different Series adjusted for days with maximum temperatures above 25 °C.

4.2.2 Simulation Series

California has 16 different climate zones as defined by the California Energy Commission. These experiments were conducted at the UCLA Energy Lab, in Climate Zone 8, close to the border with Climate Zone 6. In order to get a rough idea of how this new type of thermostat would function in different climates, a series of performance simulation runs were conducted with HEED (3).

Annual energy costs were calculated for a basic 2000 sq.ft house that meets the California Energy Code in each zone using an energy performance program called HEED. Hourly climate date is available for 14 of California's climate zones. The house is a typical California tract house with a slab on grade, stud and stucco walls, and glass area and glass type as allowed by the Code in each zone. The Series 1 controller logic was used with 0.5 air changes of infiltration, and 1.0 air changes of natural ventilation in the Code Minimum Vented building, and up to 10 air changes in the same building using the smart thermostat controlling a whole house fan. Both buildings had an air conditioner and a furnace. This meant that daytime comfort conditions (21.1 25.5 C) were always maintained in these homes. All costs were calculated using the Southern California Edison new 5-Tier rate structure, and the Southern California Gas residential energy rates averaged for the prior year.

The results (table 4) show that this type of smart whole-house fan cooling strategy saves very little money in the cooler coastal climates (Zones 1,2,5) and in the high mountains (zone 16). It is much more cost effective in all of California's southern coastal and inland climates. Notice that while it reduces electricity consumption, primarily for the air conditioner, it slightly increases gas consumption for heat.

TABLE 4: ENERGY COSTS SAVINGS

Climate	With Code Minimum Ventilation			With Smart Thermostat and Whole-house Fan			Savings
Zon	Elect	Gas	Total	Elect	Gas	Total	Diff
01	1145	700	1845	1146	701	1847	2
02	1209	338	1548	1110	347	1457	91
04	1387	295	1682	1134	296	1431	151
05	1221	152	1374	1068	272	1340	34
06	1538	65	1603	1109	65	1174	429
07	1652	36	1689	1167	37	1204	485
08	1641	44	1689	1811	48	1230	459
09	1845	77	1923	1228	87	1315	508
10	1867	251	2118	1442	254	1697	411
12	1925	179	2105	1314	283	1597	508
13	2274	167	2442	1725	259	1984	458
14	2811	105	2917	2317	108	2426	491
15	2868	187	3056	2353	192	2545	511
16	1623	682	2305	1380	938	2318	-13

This analysis shows that there would be a better return on investment for many California homeowners in a smart thermostat and a whole house fan, then to put this same amount of money in the best bank certificate of deposit (it would require a $5600 investment at 8% to equal the annual energy savings of this system, which should cost much less than that to install). The utilities should be willing to financially aid homeowners to install such systems because it will help to reduce their system peaks on the hottest periods of the year, and also shift more load into the night time hours when the fan is running to flush heat out of the building. The utility could avoid the cost of installing a peaking generator if enough of their customers install this fan-thermostat system in their homes.

5. CONCLUSIONS

When comfort low is lowered to 65 F, there is an improvement in the performance of the system because the hot hours and the maximum temperature are reduced. The reduction of comfort low, increasing thermal amplitude, is probably the single most important factor to be considered when using natural ventilation, because it increases the capacity of the building to flush the heat stored inside (to store ‘coolth’). To be effective, night temperatures should be below 21 C and close to 18 C. These are reached at night during the summer in many parts of southern California, especially in the inland and desert areas.

The building performance simulation study shows that a smart thermostat and a whole house fan would provide significant savings to Southern Californian ratepayers. The most effective rule that would be recommended for this intelligent thermostat is:

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* activate fan

Where: t_o is the temperature outside; t_i is the temperature inside; C_{f_low}, is comfort low at 65 F; and C_{f_high} is Comfort high at 78 F. Comfort low and comfort high should be adjustable by the user.

Because the test cells have a large south glazing to floor ratio (12.5%, twice the code minimum), the radiation that penetrates through this unshaded window sometimes overwhelms the cooling effect of the ventilation system. A precondition to the application of any ventilation cooling strategy is to minimize the heat gains so that the ventilation rate, regulated by the intelligent controller, is the main mechanism of heat transport.

Increasing the air change rate increases the performance of the system. When the air change rate is increased from 3.9 to 15 air changes per hour the maximum temperature was reduced by 1.5 C compared to the control building. More series have to be performed, but a typical whole house fan should probably need to supply a maximum air change rate of at least 4 changes/hour.

There is no evidence to indicate that when the system is governed by the relationship of the mass temperature with the outdoor air, the performance is better than when it is governed simply by the air temperature difference. Even though the mass in the building plays an important role as a storage medium, air temperature inside the cell is a better control variable for the ventilation system.

A potentially negative effect of using natural ventilation for cooling is that night temperatures inside the building might drop below the comfort zone. This will happen if thermostat night flushing temperatures are set below the comfort zone in order to increase the buildings ‘coolth’ storage capacity during the night and to flush out the heat gained during the day. But since these cool hours occur at night, between midnight and sunrise, it has far less impact on occupant comfort, especially because many people actually prefer to set back their thermostats to lower nighttime temperatures.

In three other tests not reported here it was shown that increasing the movement of the air inside the space reduces its stratification and increases the convective gains and losses from the thermal mass, as well as through the walls and roof surfaces of the building. In a home this can be achieved by simple means such as a ceiling paddle fan or small portable fans. However, when there is a limited amount of mass available, indoor air recirculation will discharge the ‘coolth’ from the mass too rapidly, rather than spreading its effect throughout the day. Experimental results show that best results are achieved if the recirculating fan is operated only when the ventilation (night flushing) fan has been turned on. Whenever this indoor fan is operating, the occupants’ sense of being comfortable (comfort cooling) will also increase even if air temperatures are not reduced.

An advantage of an intelligent thermostat controller that measures outdoor air temperatures, compared to a system that measures only the indoor air temperature, or a system with a fixed timer, is that the intelligent controller increases the air change rate whenever it is needed and when resources for cooling are available, rather than at times when it inadvertently heats the building.

With an intelligent thermostat controller it is possible to maximize the performance of the mass in a building, to achieve better cooling results than in a building with more thermal mass that isn’t provided with an intelligent controller for natural ventilation cooling.

6. REFERENCES

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7. ACKNOWLEDGMENTS

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