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Studies of Evaporative and Conventional Cooling of an Energy Conserving California House

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Lawrence Berkeley Laboratory University of California/Berkeley

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March 1978 LBL-6888

STUDIES OF EVAPORATIVE AND CONVENTIONAL COOLING OF AN ENERGY CONSERVING CALIFORNIA HOUSE.

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ABSTRACT

For cooling a Sacramento, California home, we study 1) higher thermostat settings, 2) insulation 3) "solar control" window shades, and 4) the use of an evaporative cooler in the place of a vapor compression cycle air conditioner. A computer program TWOZONE is used to evaluate the effect on energy consumption and peak power. We calculate that the peak cooling load can be reduced by a factor of 5 or more and the total energy by a factor of 20 or more.

Introduction

As air conditioning has moved the peak demand period for most electrical utilities from winter to summer and is forcing new power plants to be constructed, costing on the order of $1000/kw, energy and load reducing measures are becoming increasingly important. The peak loads and energy consumed can be studied by thermal modeling of a house and its HVAC systems with a computer program such as TWOZONE.

The TWOZONE program[1] uses hourly weather data and all thermal characteristics of the house being modeled to calculate the hourly heat load of the house. Most of the algorithms used in this program are ASHRAE algorithms, although some are not. As the temperature inside the house changes due to the heat flow through the surface of the building, the house HVAC controls may call for heat, cooling, nothing, or ventilation. Further, if the capacity of the air conditioning equipment is too small to meet the load during hot periods, the house temperature will increase.

The hourly weather data is obtained from TRY and CTZ weather tapes in the Cal-ERDA weather library.[2] Output from the program includes hourly information on temperatures, heat flows, heating and air conditioning loads for each hour of the day, annual equipment loads, required equipment capacities, apportioning of the loads to windows, walls, ceiling, etc., and comfort tables of internal temperatures and relative humidities.

COOLIT, the cooling subroutine, can simulate both compression cycle air conditioners and evaporative coolers. When simulating compression cycle air conditioners, the hourly heat flow into the house, its humidity ratio, its temperature, and the thermostat setting at the beginning of each hour are used to calculate the sensible and latent cooling loads during the hour, and the house temperature and humidity ratio at the end of the hour. The air conditioner parameters used in calculating the cooling loads are its cooling capacity, the air flow rate through the air conditioner, and the factory-set average coil temperature. When the routine is simulating an evaporative cooler, the ambient dry-bulb and wet-bulb temperatures and the average saturation efficiency of the cooler are used to determine the temperature of the air blown into the house from the evaporative cooler. The cooler will change speeds (if it is a multi-speed cooler) in order to maintain the temperature of the house within the specified temperature range.

COOLIT has a novel equipment "sizing" feature. Instead of reading the conventional design conditions and sizing to a single peak capacity, the size is varied each hour to meet the cooling load. The hourly sizes are compiled in a table which can then be used to select the most appropriate equipment capacity. For conventional air conditioners we find this approach more convenient; for evaporative coolers, which may not be able to maintain comfort and satisfy demand all summer; it is the only sensible approach. In addition, when an evaporative cooler is being sized, count is kept

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of the hours during which it is impossible to cool the house, i.e., hours during which the temperature of the air entering the house from the cooler is warmer than the thermostat setting.

Parametric Simulations

The house model used in the parametric simulations was a 34m^2 (1444 ft^2) box-shaped house with a flat roof (no attic), an uninsulated slab floor, and light frame walls with levels of insulation varied parametrically. Each wall was assumed to have 20% of the area in single-pane glass windows. The walls were aligned with the cardinal directions. Since this study was performed only for the cooling season (May 1 to Oct. 31), the heater thermostat was set low at 15.6°C (60°F), and the air conditioning thermostat setting was varied between 21°C and 25.6° (70°-78°F). It was assumed that the occupants of the house were energy conscious, and passively cooled the house, whenever the outside conditions permitted, by opening the windows instead of using the air conditioner. In addition, the windows were left open at night until the house cooled down to 18.3°C (65°F). The hourly weather data was obtained from the Sacramento CTZ12 weather tape in the Cal-ERDA weather library.[2]

Several parameters were varied successively. Cooling thermostat settings were 21, 23.3 and 25.6°C (70, 74, and 78°F). Walls and the roof were either uninsulated, insulated with R11 and R19 insulation respectively (R11/19 house), or insulated with R19 and R30 respectively (R19/30 house). Air infiltration was either "normal" (1/4 airchange/hour with no wind, 3/4 airchange/hour with a 4.47m/sec (10 mph) wind, or "reduced" (1/5 airchange/hour with no wind, 3/10 airchange/hour with a 4.47m/sec wind). The single-glass windows were either unshaded (U = 1.9w/(m°C) or 1.1 Btu/(hr-ft.^{2}-°F), shading coefficient = .95), or shaded with a retractable transparent reflective "solar control" shade on the inside (U = 1.04w/(m°C),(.6 Btu/(hr.-ft.^{2}-°F), shading coefficient = .18). The three cooling modes used in the program were: 1) sizing and operating an air conditioner, 2) sizing an evaporative cooler, and 3) running single and multi-speed evaporative coolers selected from a manufacturer's catalog. In addition, some evaporative cooling runs were made with the conductive/convective heat gain from the windows with reflective shades reduced by 90% when the cooler was operating. This reduction would be accomplished by allowing the air blowing in from the evaporative cooler to escape the house by blowing between the shade and the window, and assuming that this strategy would reduce the conductive/convective heat gain from the window by 90%.

Results

Air Conditioning

Tables 1 and 2 summarize the results of the parametric runs with an air conditioner to cool the house. Table 1 shows the effects of varying the thermostat setting, insulation levels in the walls and ceiling, and the window shading. Table 2 indicates the sources of heat gain into the house during the air conditioning hours.

From Table 1 it is apparent that, for houses without shaded windows, increasing the thermostat setting 2.2°C from 21° to 23.3°C (70° to 74°F) will reduce the seasonal cooling load by about 25%. Increasing the thermostat setting from 21°C to 25.5°C (70° to 78°F) will reduce the cooling load by 50%. The house which saves the greatest amount of energy by turning up the thermostat is, of course, the uninsulated house with a reduction of 3300 kwh for the season. These energy savings are progressively less for the more energy efficient houses.

Table 1 also reveals that an R11/19 house uses approximately 40% less energy than an uninsulated house for a given thermostat setting. Further increasing the level of insulation to an R19/30 house is almost ineffective; there is only a 4% savings compared to the R11/19 house when the thermostat is set at 21°C (70°F), and only a 1% savings when the thermostat is set at 25.6°C (78°F). Table 2 indicates why this is true. Once the walls and the roof have been insulated to R11 and R19 respectively, their contribution to the total cooling load is only about 10%. In comparison, the contribution of air infiltration is approximately 13%, and the contribution of the windows is about 65%! Therefore, it is apparent that the next step in reducing the cooling load once the walls and roof have been reasonably well insulated is to reduce the heat gain of the windows.

As can be seen in Tables 1 and 2, a reduced air infiltration rate does not have a very significant effect on cooling. Reducing the air infiltration rate for the R11/19 house reduces the cooling load by 6%. However, since air infiltration has been recognized as a major factor contributing to winter heating loads, most of the runs in this study assume that an energy efficient house will have a lower than normal infiltration rate; further, on the East Coast, latent loads increase the effect of infiltration by a factor of 2-3.

The final entries in Table 1 and 2 show the effect of "solar control" shades in the windows. The shades reduce the seasonal cooling load by 50%-75%, depending on the thermostat setting. Table 2 reveals that the heat gain through the windows is now about the same as the heat gain from the interal house loads (appliances, people, etc.). The seasonal energy consumption for cooling the R11/19 house has now been reduced to about 467 kwh when the thermostat is set to 25.6°C (78°F). The cost for this amount of electricity is currently about $21. It is difficult to find additional cost effective measures that can further reduce the cooling load beyond this level, other than perhaps reducing the internal loads.

Table 1 also shows the effect that various parameters have on the peak load. It was noted previously that a change of 4.6°C (8°F) in the thermostat setting would save 50% of the total cooling load for houses without window shades. This same temperature change produces a 13-20% reduction in the maximum and average peak loads for the same houses. Peak loads are reduced more effectively by insulating the house than by thermostat changes. The peak loads for the R11/19 house with low air infiltration rates are about 45% less than for the uninsulated house at the same temperature. Adding shades to the R11/19 house further reduces the load by about 40%, so that the total reduction in peak load compared to the uninsulated house at the same temperature is about 65%.

The size of the air conditioning unit required to handle 95% of the cooling loads is a useful parameter to study because the money saved in purchasing a smaller unit can be applied toward the cost of the energy conservation measures. Table 1 shows that a 3-1/2 to 4 ton unit is required for the uninsulated house, a 2 to 2-1/2 ton unit is required for the R11/19 house with unshaded windows, and only a 1 to 1-1/2 ton unit is needed for the same house with reflective shades. The capital savings are significant; a 4 ton air conditioner would probably be installed as a central air conditioning system for $2000, while a 1 ton air conditioner could be installed as a wall or window mounted unit adjacent to the main living area for $300. Cost estimates will be further discussed in a later section.

Evaporative Cooling

Tables 3 and 4 summarize the parametric runs using an evaporative cooler in place of an air conditioner. Table 3 lists the size of the cooling units needed for various house parameters, the number of hours during which the cooler will operate, and the number of "impossible" hours (during which the temperature of the air blowing into the house from the evaporative cooler would be greater than the thermostat setting). Table 4 tabulates the results of simulating commercial equipment when sized according to Table 3.

One of the most notable results to be found in Table 3 is the effect of the thermostat setting on the required size of cooler. It appears that an evaporative cooler cannot consistently keep a house in the Sacramento area much below 25.6°C (78°F). Even when the thermostat is set at 25.6°C, a very large cooler is needed (8000 cfm or more) if the windows are not shaded. In such a case, probably only the main living area would be cooled directly by the evaporative cooler. The bedrooms would be cooled indirectly by allowing the air to blow from the main living area through the bedrooms and out the bedroom windows.[4] When the windows are shaded, the size of the cooler is reduced to 6000 cfm when the thermostat is set at 25.6°C(78°F). If the air is allowed to escape the house by blowing between the shades and the windows, and then out the window, the size of the cooler can be reduced to about 4000 cfm.

Table 4 is a summary of simulations using equipment selected from a manufacturer's catalog.[5] Both 1- and 3-speed coolers of a given size were simulated. The electrical consumption for the various parametric cases ranged from a maximum of 1065 kwh for an R11/19 house with unshaded widows and a thermostat setting of 23.3°C (74°F) to a minimum of 91 kwh when the windows were shaded (with air escaping between the shade and the window) and a thermostat setting of 25.6°C (78°F). The current cost of the electricity for the above cases is $48 and $4. The evaporative cooler "EER" (energy efficiency ratio, defined as the ratio of the heat extracted to the watt-hours consumed by the motor) ranges between 8.4 and 34 Kj/watt-hr. (8 and 32 Btu/watt-hr.). In comparison the EER of an air conditioner is usually between 6.3 and 8.4 Kj/watt-hr. (6 and 8 Btu/watt-hr.). It appears that an evaporative cooler may be 1-5 times as efficient as an air conditioner. The large range (8 to 32) in EER for the evaporative cooler is discussed in ref. 6.

Peak loads are reduced significantly by using an evaporative cooler. The 4 pm "maximum" load averaged over July weather for an R11/19 house with unshaded windows, a thermostat setting of 25.6°C, and a 3-speed cooler is only 0.64 kw. When the solar control shades are added to the windows, the "maximum" drops to 0.24 kw. In comparison, the "maxima" during July for the same house but using an air conditioner, are 3 and 1.6 kw for unshaded and shaded windows respectively.

Two major criticisms about evaporative coolers are that they cannot always keep a house cool on hot or humid days and that the humidity level inside the house may get too high. It can be seen from Table 4 that, when the thermostat is set to 25.6°C, there are only about 10 hours per season during which the evaporative cooler cannot adequately cool the house. The maximum temperature reached by a house with unshaded windows is 27.8°C (82°F) at 71% relative humidity. Most people will probably feel somewhat uncomfortable under these conditions. According to Fanger comfort charts,[7] this combination of temperature and relative humidity is at the upper extreme of the comfort range, but will be considered comfortable by most sedentary people wearing light clothing if the air velocity is 1.5 m/sec or greater. The average conditions inside the house are always in the comfort range, particularly if the thermostat is set slightly lower than 25.6°C (78°F). If the thermostat is set at 24.4°C (76°F), the average relative humidity is 67%. These conditions are considered comfortable for sedentary people wearing light clothing for any air velocity. In the above analysis, the mean radiant temperature of the house is assumed to be the same as the air temperature. Often, the mean radiant temperature is higher than the air temperature because of the radiant heat gains from the windows. In this case, an occupant will feel

less comforable than this analysis indicates. The use of the reflective shades in front of the windows will then have a beneficial effect upon the comfort of the occupants since the mean radiant temperature will be lowered. A detailed analysis of this effect is beyond the scope of this paper.

Table 4 also lists the amount of water used by the evaporative coolers. A 1-speed 7860 cfm cooler on a house with unshaded windows and a thermostat setting of 23.3°C (74°F) will evaporate 52.2 m^3 (13,800 gallons) of water during the cooling season. This figure for water consumption does not include the bleed-off water necessary to keep the unevaporated salts from building up in the cooler and clogging the pads. At least one major manufacturer of evaporative coolers recommends a bleed-off rate equal to the evaporation rate. If this bleed-off rate is used, the amount of water consumed during the cooling season is 104.4 m^3, an average of .57 m^3/day (150 gallons/day).

There are several measures that can be taken to reduce the amount of water consumed. The recommended bleed-off rate may be excessive. This rate allows the salts in the cooler water to build up to twice the concentration of the salts in the supply water. The salt concentration can probably be much higher with only a negligible drop in the evaporative cooler's efficiency. A study should be conducted to determine the maximum salt buildup allowable so that the minimum bleed-off rate can be determined. Another effective measure is to have the thermostat set at as high a temperature as is comfortable. Raising the thermostat from 21 to 25°C will decrease the seasonal water consumption from the original 52.2 m^3 evaporated to 29.9 m^3 evaporated. Using a 3-speed cooler instead of a 1-speed cooler will further reduce the water consumption to 21.5 m^3 evaporated/season. Obviously, further savings can be realized by using a smaller size cooler and cooling only one section of the house, or by using several smaller coolers located in different sections of the house and running only one at a time. Finally, the use of the solar shades over the windows can significantly reduce the amount of water needed to cool the house. An insulated house with shaded windows, a 3-speed cooler, and a thermostat set at 25.6°C (78° F) will evaporate 5.3 m^3 (1400 gallons) per season. In comparison, a 9.2 m^2 (10 ft. x 10 ft.) patch of lawn will need about 11.3 m^3/season (3000 gallons/season).

Cost Analysis

The following cost analysis is mean to give a very rough idea of the cost effectiveness of fitting a house with solar control shades. This analysis assumes that the shades are going to be purchased together with the cooling equipment (the cooling equipment is not already in the house).

The cost of the solar control shades is dependent upon the shapes and sizes of the windows that the shades will cover. If each window is 3' x 5', the cost per shade is $15-30.[6] If there are four of these windows on each side of the house and if 3 sides of the hosue have shades (east, south, and west), then the total cost for the shades will be about $180-360, excluding labor. The installed cost of a 2-ton central air conditioner is over $2000. The installed cost of an 8000 cfm cooler with 3 air outlets is about $1000. The uninstalled cost of a window mounted 4000 cfm evaporative cooler is about $300. It is apparent that the combined purchase of an evaporative cooler and window shades is far cheaper than the purchase of central air conditioning. In addition, the seasonal cost for electricity used for cooling is reduced from the $100+ for air conditioning to less than $10 for the combination of evaporative cooler and shades. It appears that the purchase of an evaporative cooler and reflective window shades has an immediate economic payback to the homeowner and will save energy and money every year thereafter.

Finally, the combination of an evaporative cooler and solar control shades in place of air conditioners would benefit the utilities who would need about 66% less installed capacity to service this combination than an air conditioner. At a cost of $1000/kw installed capacity, the utility, and ultimately, society, would save about $2000/house. In addition, natural resources would be conserved, and pollution would be reduced.

FOOTNOTES AND REFERENCES

1. Wall et al., TWO-ZONE User's Manual, A. Gadgil, LBL, BEV Group report BEV 78-2.

2. Cal-ERDA Users Manual, R.M. Graven, Ed, Argonne Nat. Lab. ANL/ENG 77-03 (1978) available from ANL Code Center.

3. An example is 3M "Schotchtint", more commonly applied as a permanent self-adhesive film to transform a clear window into "solar-control" glass. The retractable shade version, however, because of the air gap, has a lower U-value, and when retracted permits the capture of winter solar radiation.

4. Since TWOZONE, in the cooling mode, assumes that the whole house is kept at a uniform temperature, these strategies were not pursued further.

5. See the Sears or Wards catalogs. However cfm ratings are taken from the McGraw-Edison catalog, which gives certified air delivery rates instead of the conventional over-estimates.

6. S.D. Gates, M.E. Thesis, LBL, in preparation.

7. ASHRAE Handbook of Fundamentals, 1977.

Table 1. Air Conditioning--Loads, Sizes, and Energy Peaks

House	T_{cool} (°F)	Seasonal Load (Therms)[a]	Peak Load (1000's Btu/h)[b]	Kwh_e[c]	$\$_{elec}$[d]	size (tons)[e]
Uninsul.	70	540	61	7200	324	4
Norm.	74	402	57	5360	241	4
Inf.	78	291	52	3880	175	3-1/2
R11/19	70	332	36	4427	199	2-1/2
Norm.	74	240	33	3200	144	2-1/2
Inf.	78	162	30	2160	97	2
R19/30	70	318	34	4240	191	2-1/2
Norm.	74	233	31	3107	140	2
Inf.	78	160	29	2133	96	2
R11/19	70	310	32	4133	186	2-1/2
Red.	74	225	30	3000	135	2
Inf.	78	152	28	2027	91	2
R11/19	70	145	19	1933	87	1-1/2
Red.	74	79	18	1053	47	1
Inf.	78	35	16	467	21	1
Shades						

a. 1 Therm = 100,000 Btu = 1.054×10^8 j
b. 1000 Btu/h = 293 watt thermal
c. Assume "EER" = 7.5 Btuh extracted/$watt_e$ power input; 7.5 is the 1979 Calif. Standard
d. Based on Calif. average residential cost of 4.5¢/kwh (Sacramento is only 1.6 to 2.2)
e. Sized to meet demand 95% of cooling hours; 1 "ton" = 12,000 Btu/h = 3.513 kw
Retail prices vary from > $2000 installed for the 2-4 ton central unit to $300 for a 1-ton window unit (see Ref. 6)

Table 2. Apportioning of Air Conditioning Loads (in Therms), for Totals in Table 1

House	T_{cool} (°F)	Windows	Walls	Roof	Infil.	Int. Loads
Uninsul.	70	207.9	86.7	155.1	38.3	51.6
	74	157.9	60.5	119.5	28.9	35.4
	78	117.1	40.6	88.4	20.5	24.2
R11/19	70	210.7	14.1	17.1	42.7	47.1
NI	74	155.8	8.5	13.2	28.6	34.1
	78	106.8	4.6	9.2	19.7	21.6
R19/30	70	211.1	8.2	9.0	42.0	47.8
NI	74	157.5	4.4	7.9	36.5	26.3
	78	110.4	1.7	6.4	17.0	24.8
R11/19	70	211.0	14.3	17.9	16.5	50.0
RI	74	156.0	8.7	13.4	11.2	35.7
	78	106.9	4.6	9.3	8.0	23.4
R11/79	70	52.7	13.1	17.3	9.4	52.1
RI	74	26.0	6.5	10.1	8.5	27.6
Shades	78	9.5	2.4	4.3	3.8	14.7

a. Internal loads appear to vary because they are counted only when a-c operates
b. NI = normal infiltration; RI = reduced.

Table 3. Evaporative Cooler Sizing

Description	T_{cool} (°F)	Sizing (CFM)[a]	Total Hours	Impossible Hours
Uninsulated NI	78	12000	988	5
R11/19	70	>30000	1743	461
RI	74	>30000	1319	115
	78	8000	956	5
R11/19	70	>30000	1515	461
RI	74	>30000	858	115
Shades	78	6000	405	5
R11/19	70	>30000	1515	461
RI	74	>30000	858	115
Shades w/ convection reduced	78	4000	405	5

a. 1 cubic foot per min. (cfm) = $.47 \times 10^{-3} m^3$/sec.
b. Hours when T(evap) > T(cool) are called "Impossible".

Table 4. Seasonal Operation of Evaporative Coolers sized in Table 3, for R11/19 house only.

House	T_{cool} (°F)	Size (CFM)	No. of Speeds	Kwh_e	$\$_e$[a]	EER	Gal H_2O	Hours	Imposs. Hours	T_{max}@RH	$RH_{av.}$	RH_{max}@T
Unshaded windows	74	7860	1	1065	48	14.8	13800	1253	176	82°@71%	71	84%@70°
			3	818	37	22.1	11200	1296	184	82°@71%	68	83%@70°
"	78	7860	1	509	23	18.6	7892	905	11	82°@71%	67	80%@74°
			3	378	17	32.8	5663	937	11	82°@71%	64	78%@77°
Shades w/ reduced conduction	74	7860	1	691	31	8.0	9283	785	112	81°@73%	72	84%@70°
			3	469	21	12.9	6677	818	115	81°@73%	72	84%@77°
	76	5180	3	190	9	22.9	3033	600	34	81°@72%	67	80%@76°
"	78	5180	3	101	5	29.2	1653	401	4	81°@72%	65	79%@78°
"	78	3930	1	156	7	16.5	2215	377	8	81°@72%	67	79%@76°
			3	91	4	31.7	1412	405	9	81°@72%	64	79%@78°

a. See footnotes in Tables 1 & 3.
b. Includes only the amount of water evaporated, no bleedoff.

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